



**THERMAL TREATMENT OF PLASTIC
MEDIA BLASTING WASTE**

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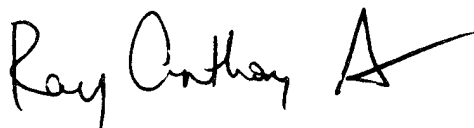
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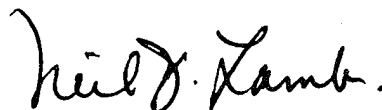
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PREFACE

This report was prepared by the Energy Technology Division, Oak Ridge National Laboratory, P.O. Box 2009, Oak Ridge, TN 37831-8088 , for the Environics Directorate (AL/EQ), Suite 2, 139 Barnes Drive, Tyndall Air Force Base, Florida 32403-5319.

This report describes the thermal treatment of plastic media blasting. Plastic media blasting (PMB) is a process employed by the Air Force and others to strip protective coatings from aircraft and other equipment. The waste is made up of about 90% plastic medium and 10% paint residue, when garnet is not used. The plastic medium, being an organic material, can be thermally decomposed into gaseous components that can be released, thus reducing the waste to be disposed of to a fraction of the untreated waste. The results of a pilot test in a fluid-bed reactor treating two combination streams of PMB waste are presented, including life cycle and cost analyses associated with operation. The cost analyses indicates the fluid bed reactor thermal treatment process can be cost-effective in some cases when compared to direct landfilling.

The project was initiated under Capt Helen Jermyn and completed under Lt Phil P. Brown and Lt Ray A. Smith of AL/EQS at Tyndall AFB, Florida.

EXECUTIVE SUMMARY

A. OBJECTIVE

This document provides information regarding the thermal treatment of plastic media blasting (PMB) waste generated during aircraft protective coating removal. The information is to help the Air Force decide whether and how to install a thermal treatment system for PMB waste generated by Air Force.

The information addresses six major areas:

1. Mass and volume reduction of the waste.
2. Retention and releases of hazardous components and compliance with laws, regulations, and guidelines.
3. Economic analysis, and a restricted comparison with current waste disposal applications.
4. cursory environmental impact.
5. Initial estimate of possible impact of "pending" and other regulatory changes.
6. A conceptual design report suitable for providing design specifications for a production scale unit.

B. BACKGROUND

Plastic media blasting (PMB) is a process employed by the Air Force and others to strip protective coatings from aircraft and other components. This process employs plastic particles which are impinged on the coatings to remove them. There are several different waste streams generated by the process. At Hill Air Force Base, which was used as the sample base, and the source of waste used for testing, the waste amounts to an annual mass of approximately 125 metric tons. This waste is a fine powder consisting of paint residue and flakes and plastic blasting media. Because this waste contains chromium, cadmium, and other hazardous components, it is considered a RCRA hazardous waste, and therefore must be stabilized to meet regulatory leachability criteria. To reduce the cost and improve the economy of plastic media blasting, a reduction in mass and volume of the waste is considered. The waste is made up of about 90% plastic medium and 10% paint residue, when garnet is not used with the plastic medium. The plastic medium, being an organic material, can be thermally decomposed into gaseous components that can be released, thus reducing the waste to be disposed of to a fraction of the untreated waste [1,2].

An earlier project to treat PMB waste employed a rotary kiln to decompose the organic matter. However, during the pilot test, the PMB waste foamed and adhered to the kiln chamber. This result is unacceptable and a decision was made to use a fluid bed reactor process to thermally decompose the PMB waste.

C. SCOPE

The results of a pilot test in a fluid-bed reactor treating two combination streams of PMB waste are presented. Included are life cycle and cost analyses associated with operating a fluid bed reactor at Hill Air Force Base to treat the PMB waste generated during paint removal. Section I is an overview of the technology. Section II describes and characterizes the waste generated by the PMB operations. Section III describes the test protocol, test results, ash stabilization, and cost analysis associated with the fluid bed reactor process. Section IV describes a life cycle analysis associated with installation and operation of a fluid bed reactor located at Hill Air Force Base. The conclusions and recommendations are listed in Sections V and VI.

D. PILOT TEST DESCRIPTION

Samples from the two largest Hill Air Force Base PMB waste streams, designated as B48 and B70, were blended together to form a representative sample for the pilot testing. The composite waste samples were analyzed for elemental composition, heat content, particle size distribution, and total metals. The pilot-scale testing of the fluid bed reactor was conducted during a three day period in September 1994. The fluid bed reactor used in this study, to process the composite samples, is owned and operated by Hazen Research Inc. of Golden Colorado. The prime parameters that were controlled were bed temperature and final oxygen concentration. The waste was fed into the fluid bed reactor at an average rate of 10 kg/h. When the waste entered the fluidized bed of silica media, it was combusted into gas and ash. The ash was collected using a cyclone separator and a baghouse. The residence time of the combustion gas in the fluid bed reactor was about 3.5 seconds in all test cases. The bed inlet gas velocity was maintained at approximately 0.85 m/s in the first two days of test runs. This velocity was increased to 0.98 m/s the final day of testing. Process operating data and emission sampling were gathered at the operating conditions. Emissions of carbon monoxide (CO), total hydrocarbons (THC), oxides of nitrogen (NO_x), and sulfur dioxide (SO₂) were measured as a function of both bed temperature and off-gas oxygen concentration. Grab samples of the ash were analyzed for particle size distribution, bulk density, and total metals. The ash captured in the cyclone separator and baghouse from all three days of testing was combined to form a sample for stabilization testing. This ash composite sample was mixed with varying quantities of fly ash, blast furnace slag, Type II Portland cement, sodium sulfide, and water to form a solid structure. Six specimens, each having a different batch formula, were made and subsequently tested for metals leachability.

E. RESULTS

The PMB composite waste sample generated at Hill Air Force Base had a mean particle size of 200 μ m and a heating value of 21 MJ/kg. This waste sample contained significant concentrations of cadmium, chromium, barium and lead, which are all listed as hazardous by the Resource Conservation and Recovery Act (RCRA). Other metals present in significant concentrations included potassium and sodium. No problems were experienced during the first two days of operation. However, during the higher velocity and higher temperature (third day) operation, visible grains of bed media were observed in the cyclone ash, indicating that a bed velocity of 0.98 m/s was too high. During the third day there was also some bed media agglomeration.

The ash mass balance indicated that the ash recoveries from the cyclone and baghouse were less than 85 mass percent. The emission monitoring indicated that the combustion efficiency tended to increase with increasing temperature or increasing oxygen concentration. One conclusion is that the fluid bed reactor needs to operate at a minimum bed temperature of 800°C and a minimum offgas oxygen concentration of 7 mole percent in order to meet the regulatory emission limits.

The majority of the residual ash (greater than 97 mass percent) formed during combustion was collected in the cyclone. However, the concentration of metals typically considered to be volatile (mercury, cadmium, lead, potassium, and sodium) was higher in the baghouse ash. All of the ash collected was high in carcinogenic metal content. The leachability tests performed on the waste composite ash showed that four of the six batches tested were within the regulatory limits. The results indicated that mixtures containing ash, Type II Portland cement and blast furnace slag performed best.

F. LIFE CYCLE COST ANALYSIS

The cost-effectiveness of the thermal treatment option for the disposal of PMB waste is compared with the direct landfilling option using a life cycle cost (LCC) analysis. Under base-case assumptions, most of which are appropriate for Hill Air Force Base, the estimated total LCCs of the thermal treatment and the direction landfilling options are \$6.4M (\$848/ton) and \$1.6M (\$205/ton), respectively. The cost savings, associated with thermal treatment, is considered large enough to be more favorable than direct landfilling in some cases. Most of the life cycle cost for the thermal treatment process is due to capital and maintenance expenditures. A smaller thermal treatment system with a better operating factor

reduces the total LCC substantially.

LCC analyses indicate that thermal treatment is economically feasible for high waste-processing rates and a combination of high T&D cost coupled with low transportation distances (and vice versa). Another important consideration is the cost of waste separation. The multiwaste processing capability associated with the thermal treatment option can make this option much more cost-effective than direct landfilling.

G. ENVIRONMENTAL IMPACT ANALYSIS

A brief and preliminary environmental impact analysis was conducted for a fluid bed reactor thermal treatment process and compared with direct landfilling of untreated waste. There are environmental concerns associated with both options. A fluid bed reactor thermal treatment process is subject to emission regulations by the EPA which are expected to become even more stringent in the future.

H. DESIGN AND OPERATIONAL CONSIDERATIONS

Important design and operational features include the waste profile, operating factor, life cycle cost and environmental impact. Each of these features must be considered to license and operate a thermal treatment process at a specific capacity. The pilot study showed that fluid bed reactor can be used to thermally reduce the volume of solid PMB waste requiring disposal. However, the two key issues that determine whether this process is installed will be the life cycle cost and the environmental regulatory climate.

I. CONCLUSIONS

The pilot test demonstrated that the volume or mass of solid PMB waste, such as generated at Hill Air Force Base, can be reduced by a factor of 20 by treatment in a fluid bed reactor. During the pilot test operation, the reactor met the emission regulatory standards associated with the gaseous combustion products. The ash residue formed during combustion can be stabilized to meet regulatory standards for leachability by encapsulating the ash in a solid cement-slag waste form.

The life cycle cost analysis indicates that the fluid bed reactor thermal treatment process can be cost-effective in some cases when compared to direct landfilling, even though capital and maintenance costs are relatively high. Several environmental concerns exist with thermal treatment of PMB wastes. These concerns need to be further investigated and addressed before installing a fluid bed reactor thermal treatment process.

J. RECOMMENDATIONS

We recommend that this study be used as a basis for determining whether to thermally treat PMB waste to reduce the volume of solids to be disposed. This study includes an economic evaluation with ancillary environmental impact information. There are however, additional concerns that need further consideration. These concerns include: (1) Future outlook of continued use of PMB and possible substitutes. (2) Anticipated changes in quantities of waste. (3) Possible regulatory changes. (4) Specific location licensing concerns, (5) possibility of a regional or even national facility, and (5) Inclusion of other wastes in the treatment.

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LIST OF ACRONYMS AND ABBREVIATIONS

BIF	Boiler & Industrial Furnace
CEMS	Continuous Emission Monitoring System
CETRED	Combustion Emissions Technology Resource Document
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
EI	Environmental Information
EPA	Environmental Protection Agency
HAFB	Hill Air Force Base
HCN	Hydrogen Cyanide
LCC	Life Cycle Cost
NAAQS	National Ambient Air Quality Standards
NM	Not Measured
NO _x	Nitrogen Oxides
NPV	Net Present Value
O ₂	Oxygen
OMB	Office of Management and Budget
PCDD	Polychlorinated Dibenzo-p-dioxins
PCDF	Polychlorinated Dibenzofurans
PMB	Plastic Media Blasting
PMBW	Plastic Media Blasting Waste
RCRA	Resource Conservation and Recovery Act
T&D	Treatment and Disposal
TCDD	Tetrachlorodibenzo(para)dioxin
TCLP	Toxicity Characteristic Leaching Procedure
THC	Total Hydrocarbons
USEPA	United States Environmental Protection Agency
Utah	State of Utah Air Toxics Policy

SECTION I INTRODUCTION

A. OBJECTIVE

The objective of this study was to evaluate the feasibility and practicality of using a fluid bed reactor to reduce the mass or volume of Plastic Media Blasting (PMB) waste requiring stabilization and thus reduce cost. This process must meet current and potential EPA emission guidelines, and the treated waste must comply with RCRA stabilization requirements. A life cycle cost analysis and a partial environmental impact analysis are also included. These efforts will serve to facilitate a decision by the Air Force whether to install a thermal treatment system for the PMB waste generated by the United States Air Force.

B. BACKGROUND

Plastic media blasting (PMB) is a process used by the Air Force to remove protective coatings from aircraft and other components. This process removes coatings from a surface by pneumatically impinging a stream of plastic particles to a surface. These particles are used to remove topcoats and primers without harming substrates. The plastic media blasting process is used by the Department of Defense to replace chemical stripping agents previously used for removing the coatings from military aircraft and aerospace components. After several usages the plastic medium and the removed coatings end up as waste. The Air Force has several different waste streams which are generated by this process. At Hill Air Force Base, which was used as the sample base and the source of waste used for testing, PMB waste amounts to an annual mass of approximately 125 metric tons. This waste is a powder consisting of paint residue and plastic blasting medium. Because this waste contains chromium, cadmium, and other hazardous components, it is considered a RCRA hazardous waste, and therefore must be stabilized to meet regulatory leachability criteria. To reduce the cost and improve the economy of PMB waste management and disposal, a reduction in mass and volume are considered. The waste is made up of about 90% plastic medium and 10% paint residue, when garnet is not used with the plastic medium. The plastic medium, being organic, can be thermally decomposed into gaseous components that can be released, thus reducing the waste to be disposed of to a fraction of the untreated waste [1,2].

An earlier project to treat PMB waste employed a rotary kiln to decompose the organic matter. However, during the pilot test, the PMB waste foamed and adhered to the kiln chamber. This result was unacceptable and a decision was made to use a fluid-bed reactor process to thermally decompose the PMB waste.

A survey of the PMB waste generated at Hill Air Force Base was conducted to determine the most representative sample for pilot testing. The two largest waste streams consist of paint residue and plastic media and are denoted as B48 and B70. Samples from these two waste streams composited to form a representative sample for pilot testing. A third waste stream, B50, contains paint chips, plastic blasting medium, and approximately 50 mass percent garnet. The B50 waste was characterized as part of this study, but was not included in the pilot testing.

A pilot-scale fluid bed reactor was used to treat the PMB waste samples. The reactor ran for three days under various operating conditions. During testing, the emissions were monitored, and the residual ashes were collected and analyzed. The ash was mixed with stabilizing agents, stabilized, and tested for metals leachability. The stabilization results are further described in a report by Focus Environmental, Inc. [1].

C. SCOPE/APPROACH

The approach involved selecting a representative sample for testing. It was decided that the representative sample would consist of the two types most commonly used at Hill Air Force Base. The

two waste streams selected do not contain inert filler, such as garnet. The fluid bed reactor, used in this pilot-study, is owned and operated by Hazen Research, Inc. of Golden Colorado. This reactor was equipped with emission monitors and controls as well as sampling equipment in order to monitor and evaluate the process during operation.

The pilot-scale test program consisted of three days of testing, 12 hours per day each. The key test parameters that were varied during the pilot-test were bed temperature and offgas (exit) oxygen concentration. The target bed operating temperatures were 760, 870, and 980 °C which were maintained at day 1, day 2, and day 3 respectively. The pilot process was operated at three off-gas oxygen concentrations (5.5, 7.0, and 9.0 mole percent) for each bed operating temperature. Process emissions were monitored during each test condition.

The resulting ash residues from the 3 days of testing were analyzed and combined for stabilization testing. The ash was mixed with several stabilizing agents in varying amounts and it was determined that the EPA metals leachability test requirements can be met.

Analyses of life cycle costs and environmental impact were performed to provide additional information needed to decide whether to employ a thermal treatment process to manage the PMB waste streams. The cost savings associated with operating a thermal treatment process are more favorable than direct landfilling in some cases. This is especially true for high waste-processing rates and high treatment and disposal (T&D) costs coupled with low transportation distances. However, because the waste generation rate for Hill Air Force Base is low (123 tons annually), thermal treatment may not be cost effective when limited to this application. The environmental impacts associated with thermal treatment and direct landfilling are inconclusive but it is reasonable to expect that regulations governing landfill disposal will become stricter, thereby making thermal treatment a more desirable option.

SECTION II WASTE PREPARATION

A. WASTE DESCRIPTION

Hill Air Force Base in Davis County, Utah was selected by the Air Force as a sample PMB user and waste generator. This base generates approximately 125 metric tons of this waste annually. Hill Air Force Base uses predominantly urea formaldehyde (Type II) and acrylic (Type V) as the stripping medium. The majority of the spent media goes into one of four different waste streams, which are denoted as follows:

- B48 waste - contains Type II media and coating residue
- B49 waste - contains Type II media, coating residue, and about ten mass percent garnet or silica
- B50 waste - contains Type II media, coating residue, and between 50 and 80 mass percent garnet
- B70 waste - contains Type V media and coating residue

The waste streams B48 and B70 consist only of paint chips and the plastic blasting media, while the other two streams contain varying concentrations of inert materials such as garnet or silica. The B48 and B70 wastes accounted for approximately 40 and 28 mass percent of the total PMB wastes generated in 1993, respectively. Because the other two wastes contain noncombustible waste materials, it was decided to make a representative sample for testing from the B48 and B70 waste streams [1].

B. WASTE PREPARATION AND CHARACTERIZATION

Samples of the B48, B70, and B50 wastes were obtained from Hill Air Force Base. Samples B48 and B70 were blended together to obtain representative waste sample for testing. This composite sample consisted of 46 mass percent B70 and 54 mass percent of B48 which was well blended. The B50 and composite waste samples were analyzed for particle size distribution and elemental contents (metals). Another set of samples were combusted in a muffle furnace and the residual ashes were analyzed for elemental analysis. Cadmium, chromium, barium, and lead, which are regulated by RCRA for their leachability, were present in significant concentrations as shown in Table 1. These metals are components of the aircraft protective layers that are being removed. Other elements present in significant concentrations included potassium, sodium, sulfur and phosphorous. The fusion temperature was also determined for the waste ash. In an oxidizing atmosphere, the ash began melting at 1275 °C and became fluid at 1385 °C. Because these temperatures are substantially higher than the planned operating temperature of the fluid bed reactor, the melting of the residual ash from the waste blend was not expected to be a concern. A thermogravimetric analysis was performed on the composite waste sample which indicated that significant mass loss occurred between 250 and 600 °C which resulted in a final solid product that was equivalent to approximately 4.5 percent of the starting mass [1].

Another sample of the waste was used to determine the explosive characteristics of the waste dust in air. The results [1] indicated that the waste dust may explode under certain conditions. The maximum pressure produced during the test (77 kPa) indicates that all dust-containing vessels should be grounded and fitted with an explosion relief vent. However, because the resulting explosion was classified as weak, the size of the relief vent may be small. The test results also indicated that the waste powder is relatively insensitive to electrostatic charges. Therefore, there is no need for operators to wear antistatic clothing. We do recommend, however, that the pneumatic transfer line to the fluid bed reactor be electrically conductive and grounded.

Table 1. Metal Content of Roasted Waste Samples

Important metal impurities	B48/B70 Waste composite		B50 Waste	
	Initial waste	Ash	Initial waste	Ash
RCRA listed hazardous metals, ppm				
Cadmium	985	5000	85	500
Chromium	1100	24450	440	550
Barium	1250	325	245	320
Lead	320	28700	725	940
Other metals, ppm				
Aluminum	3750	29500	74050	106500
Calcium	1000	26750	5200	8660
Iron	1680	30800	165000	239500
Magnesium	245	17900	8535	12800
Silicon	7350	128000	83700	127500
Sodium	150	1275	255	430

RCRA = Resource Conservation and Recovery Act

SECTION III PILOT TEST DESCRIPTION AND EXECUTION

A. BED MEDIA SELECTION

Various inert bed materials are used in fluid-bed combustion processes, the two most common are alumina and silica. Silica is used because it is readily available and inexpensive, while alumina is used in situations where the ash and silica react with one another. Several tests were performed on silica and alumina media to determine which to use during the pilot testing. Cold flow fluidization tests were performed with silica and alumina media to determine the gas flow necessary for optimum fluidization. Tests were conducted using a laboratory-scale glass fluid-bed vessel equipped with a cyclone and baghouse to contain fine particles that escape the fluid-bed vessel. The fluidization study showed that the optimum fluid characteristics correlated with an air velocity of approximately 0.76 m/s and 0.61 m/s for silica and alumina respectively. Carryover of the bed media was 0.03 mass percent for the silica media and 5.5 mass percent for the alumina. Silica was selected because the gas velocity was higher and the bed medium carryover was less. A high air velocity is desirable because this allows more oxygen for combustion, resulting in higher feed capacities. Differential thermal analyses were also performed on the silica media and the composited waste ash to determine whether the ash would react with the silica during combustion. These results gave preliminary indications that the waste ash and silica would not interact detrimentally. As a result of these tests, silica was selected as the fluidizing medium for the pilot scale fluid bed tests [1].

B. DESCRIPTION OF TEST EQUIPMENT

Figure 1 is a flow diagram of the pilot-scale waste-processing system used in this study. The pilot-scale process consisted of four major components: (1) waste-feed system, (2) fluid-bed reactor, (3) cyclone separator and baghouse, and (4) process monitoring instrumentation. All of the components were constructed of materials designed to withstand operating conditions.

1. Waste-Feed System

A hopper with a capacity of 0.03 m³ was used to store the test waste powder. The waste was discharged from the hopper via a rotary valve to a constant-speed screw feeder. This screw-feeder was equipped with a 5 cm diameter screw which transferred the waste from the discharge of the rotary valve to a 1.3 cm diameter transport line. The waste material was pneumatically conveyed through the transport line to the fluid bed reactor. The fluid bed reactor was operated under a positive pressure, and the rotary valve located at the hopper discharge prevented backflow. The feed rate was controlled by varying the speed of the rotary valve and was determined by measuring the mass change of the hopper per unit time.

2. Fluid-Bed Reactor

The fluid-bed reactor contains the chamber in which the organic part of the waste is thermally decomposed into gaseous products. The waste combustion system had a windbox, fluidized bed, and freeboard. The three components were lined with refractory insulation and joined together.

The windbox is an L-shaped cylindrical chamber used to provide a space to preheat ambient air, which serves to preheat the fluidizing media at start up. The waste material had sufficient heat content to sustain the reactor at the desired temperature. The windbox burner was used only during startup.

The fluidized-bed combustion chamber was cylindrical, 38 cm in diameter and approximately

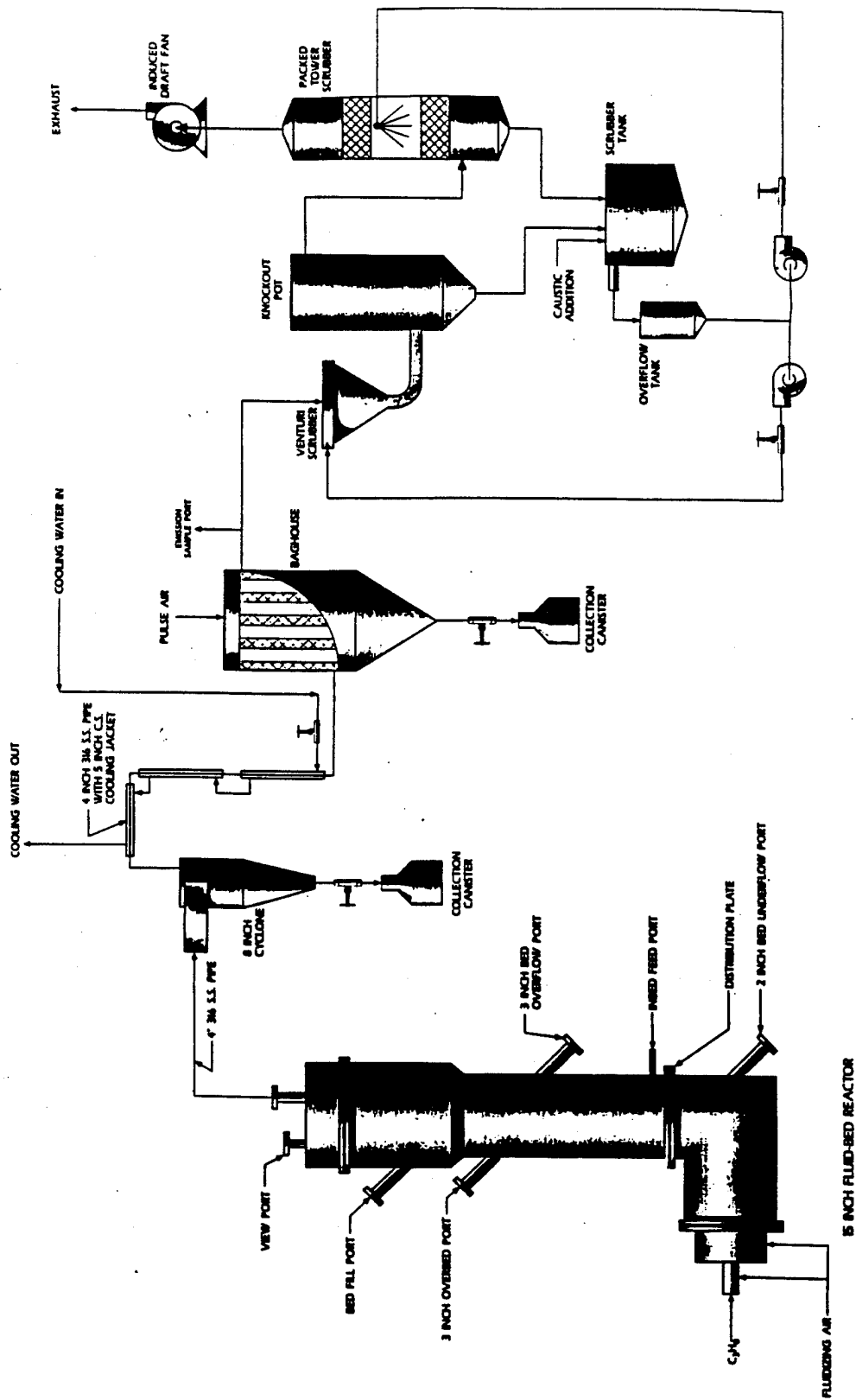


Figure 1. Flow Diagram for Fluid Bed Reactor Pilot Test Process

152 cm tall. The chamber held 160 kg of silica bed media. Waste was fed continuously into the chamber through a port located above the base of the fluidized bed.

The freeboard zone is designed to provide additional residence time for completion of combustion and to minimize carryover of the bed medium exiting the reactor chamber. An air pollution control system was mounted at the top exit of the freeboard.

3. Air Pollution Control

The air pollution control system consisted of a cyclone separator, dry quench, baghouse, induced draft fan, and stack. The purpose of the cyclone separator is to remove particles from the combustion gas exiting the fluid bed reactor. The coarse particles are discharged and contained within an enclosed collection canister. After exiting the cyclone, the gas entered the dry quench. The dry quench consisted of a series of heat exchangers, whose purpose was to cool the combustion gases so they could be handled by the baghouse. The baghouse was used as a final particulate removal device. It consisted of fiberglass bags which served as filters. An induced draft fan was used to maintain the air pollution control system under negative pressure and to draw the cleaned combustion gas from the process [1].

4. Process Monitoring System

The temperatures and gas pressures were measured continuously at various points of the process. The locations of the monitoring instruments are shown in Figure 2. The combustion gas was continuously sampled at the outlet of the baghouse and analyzed for O_2 , CO_2 , CO , SO_2 , total hydrocarbons, and NO_x . The pilot-scale facility was equipped with on-line instrumentation to obtain process operating data. Process temperatures and gas composition data were monitored and recorded continuously. A data acquisition system was used to monitor and record selected process data.

C. TEST METHODOLOGY

1. Shakedown Testing

Two days of shakedown testing were conducted. The shakedown testing allowed for familiarization with the system and process adjustments and fine tuning.

2. Experimental Test Matrix

The test program involved 3 days of testing. A test run consisted of operating the process for 12 hours followed by overnight shutdown. Each test consisted of startup, operation, shutdown, and sampling. The key control parameters were the bed temperature and offgas oxygen concentration as shown in Table 2. The target bed operating temperatures were 760, 870, and 980 °C in that order. The process was operated at three offgas oxygen concentrations (5.5, 7.0, and 9.0 mole percent) for each bed operating temperature. For each test condition, emission samples were measured for CO , SO_2 , total hydrocarbons, and NO_x . For those test conditions which corresponded to an oxygen level of 7.0 mole percent, additional measurements were taken for metals, particulates, volatile organics, semivolatile organics, dioxins and furans, chlorine, and hydrogen cyanide (HCN).

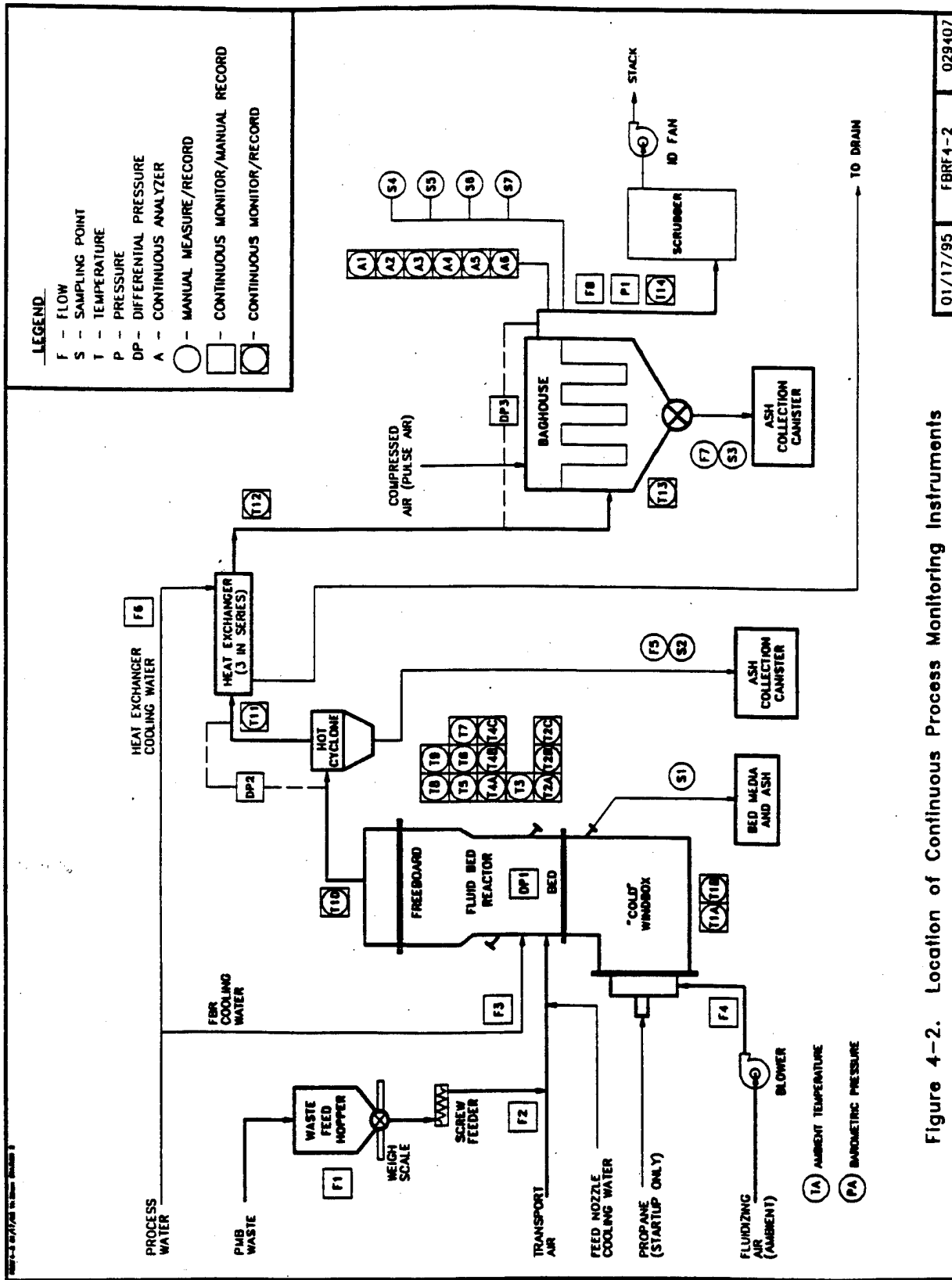


Figure 4-2. Location of Continuous Process Monitoring Instruments

Figure 2. Location of Process Monitoring Equipment

Table 2. Experimental Design Test Matrix

	Bed temperature		
	760 °C (day 1)	870 °C (day 2)	980 °C (day 3)
Offgas oxygen concentration	5.5	5.5	5.5
	7	7	7
	9	9	9

3. Experimental Procedure

The test was started by heating the reactor and allowing it to reach the target temperature. The waste feed and air flow rates were adjusted to maintain off-gas oxygen concentration. The bed temperature was maintained by adjusting the injected bed (cooling) water rate. The system was run for at least one hour at steady state to record offgas concentrations. The respective first runs were begun at oxygen exit concentrations of 5.5 mole percent. After collecting data at the lowest oxygen off-gas concentration (5.5 mole percent), the waste feed rate was decreased until the oxygen concentration reached approximately 7.0 mole percent. The cooling water feed rate was reduced in order to maintain the bed temperature. The airflow was held constant to maintain fluidization. Following 30 minutes of steady state operation, the off-gas emissions were sampled. Sampling was performed at the baghouse outlet. The sampling procedures followed the guidelines of EPA Method 0030 for volatiles (SW846, Third Edition, 1986) and Method 0010 for semivolatiles, dioxins, and furans. The process was repeated for off-gas concentration of approximately 9.0 mole percent. At the end of each test run, a sample of the bed medium was taken and analyzed for particle size distribution, bulk density, and total metals. The tests were repeated at each of the three bed test temperatures.

SECTION IV TEST RESULTS

A. PILOT TEST OPERATION

A summary of the fluid bed reactor pilot test operating data is presented in Table 3.

Table 3. Pilot Test Operating Data

Test parameter	Day 1			Day 2			Day 3		
	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Fluid bed reactor									
Thermal duty, GJ/h	0.25	0.21	0.18	0.22	0.20	0.18	0.25	0.21	0.17
Waste feed rate, kg/h	12.0	10.1	8.7	10.3	9.4	8.4	11.8	10.1	7.9
Air flow rate, m ³ /min	1.23	1.22	1.25	1.12	1.12	1.12	1.21	1.19	1.14
Inlet gas velocity, m/s	0.88	0.85	0.88	0.85	0.85	0.85	1.01	1.01	0.94
Bed temperature, °C	779	780	775	879	877	876	965	967	965
Bed inlet pressure, kPa	110	110	110	110	110	110	110	110	110
Bed residence time, s	1.8	1.8	1.7	1.8	1.8	1.8	1.5	1.5	1.6
Bed pressure drop, kPa	7.3	7.5	7.2	7.1	7.1	7.1	7.2	7.3	7.2
Baghouse									
Inlet gas temperature, °C	194	179	188	171	183	178	188	190	183
Pressure drop, Pa	12	12	12	12	12	12	12	12	12

1. Waste Feed Rates and Thermal Duty

The average waste feed rate for the three days of testing was approximately 10 kg/h. This value corresponded to an average thermal duty of approximately 0.21 GJ/h. The residence time of the combustion gas was determined to be about 3.5 seconds.

There were no significant problems with the pneumatic transfer of the waste material to the fluid bed reactor. The waste-to-air mass ratio in the transfer line was 3.3 kg/kg or 3.7 kg/m³ waste mass to air volume flow rate.

2. Bed Gas Velocity Measurements

The bed inlet gas velocity was maintained at approximately 0.85 m/s for the first two days of test runs. The velocity was increased to approximately 0.98 m/s on the final day of testing. No problems were encountered during the first two test runs; however, during the third run, bed media was collected from the cyclone ash. This suggests that the bed velocity was too high during the third run. The results indicate

that a velocity of 0.85 m/s is preferable, although no flow velocity optimization was done. Higher waste feed rates and associated air flow rates increase the reactor utilization.

3. Ash Recoveries

The mass of ash fed into the process for each test was determined by multiplying the ash concentration of the waste feed (4.5 mass percent) by the total mass of waste material fed into the process. The ash reclaimed from the cyclone and baghouse contained some of the silica bed media, which had to be removed to obtain an accurate ash mass. The actual ash recoveries were determined to be less than 85 mass percent. This implies that ash had accumulated in the bed media. The bed medium was visually discolored, which further indicates that the ash was contaminating the bed medium particles.

The collection efficiency of the cyclone was determined by comparing the mass of ash collected from the cyclone with the total ash captured. The collection efficiency averaged 97 percent for all of the test runs.

4. Bed Medium Characterization

The mean particle size of the starting bed medium was between 490 and 520 μm . After the test, the size range of bed particles was between 212 and 850 μm . Samples of bed medium taken at various times during the test showed that the particle sizes and metals concentration tended to increase with processing time. These results indicate that the bed media became increasingly contaminated with the waste ash during pilot testing.

Bed modifiers are often added to fluid-bed systems to protect bed media against agglomeration with the ash, examples include kaolin clay. The results indicate that a full-scale process must be equipped with the capability of adding a bed modifier to prevent or minimize agglomeration of the bed media.

B. BAGHOUSE CONTINUOUS EMISSION SAMPLING

The offgas from the process was monitored continuously for O_2 , CO_2 , CO , NO_x , SO_2 , and total hydrocarbons. The last four are criteria pollutants that impact the permitting of a full-scale process. The pilot test evaluated the effect of bed temperature and offgas O_2 concentrations on the offgas concentrations of these four criteria pollutants.

1. Carbon Monoxide and Total Hydrocarbons (THC)

Carbon monoxide and total hydrocarbons are indicators of combustion efficiency. The regulatory limit for CO for combustion systems is 100 ppm on a 60 minute rolling average basis. Under the boiler and industrial furnace regulations, combustion systems processing hazardous waste must meet the 100 ppm CO limit or an alternative 20 ppm THC limit. The THC limit is evaluated on the same basis as CO.

Combustion efficiency typically increases with increasing combustion temperature or increasing oxygen concentration in the combustion chamber. The results from the pilot test supported this statement. Figure 3 represents the CO concentrations in the offgas as a function of bed temperature and offgas O_2 concentration. The test cases performed at the lower O_2 concentration (5.5 mole percent) exceeded the 100 ppm CO limit, while the tests performed at O_2 concentrations of 7.0 and 9.0 mole percent were within the required CO limit. However, the data indicate that best operating conditions occurred for bed temperatures higher than 800°C and offgas O_2 concentrations greater than 7.0 mole percent in order to be safely within the required limit.

The THC monitor was not functional during the second day of testing (bed temperature of 877 °C). But it was noted that the THC results from the first and third days exhibited the same trend as the offgas CO concentration. All of the test conditions were well within the THC limit except for the test case corresponding to a bed temperature of 779°C and offgas oxygen concentration of 5.7 mole percent.

2. Oxides of Nitrogen and Sulfur

Emissions of NO_x were generated from the nitrogen in air (thermal NO_x) and also the nitrogen present in the waste feed (fuel NO_x). Thermal NO_x formation is primarily a function of the combustion chamber temperature, while the fuel NO_x formation is a function of the combustion chamber temperature, nitrogen concentration in the waste, and the oxygen concentration in the offgas.

Nitrogen oxide emissions are regulated under the National Ambient Air Quality Standards (NAAQS) program implemented through the Utah Air Pollution Regulations. Under the NAAQS program, a fluid bed reactor located in Davis county must not generate over 36 metric tons of either NO_x or SO_2 annually.

The NO_x stack emissions were calculated to be 1.83 grams of NO_x for each 100 grams of waste feed. For the 125 metric tons of waste generated annually at Hill Air Force Base, this amounts to less than 3 metric tons of NO_x annually. This is well below the significant net emissions increase as stated by NAAQS. Hill Air Force Base can, probably, process up to 1500 metric tons of PMB waste annually and not exceed the 36-metric ton limit. The SO_2 emissions amounted to less than 0.5 metric tons generated annually from processing 125 metric tons of waste. This also is well within the significant net emissions standards set by NAAQS [1].

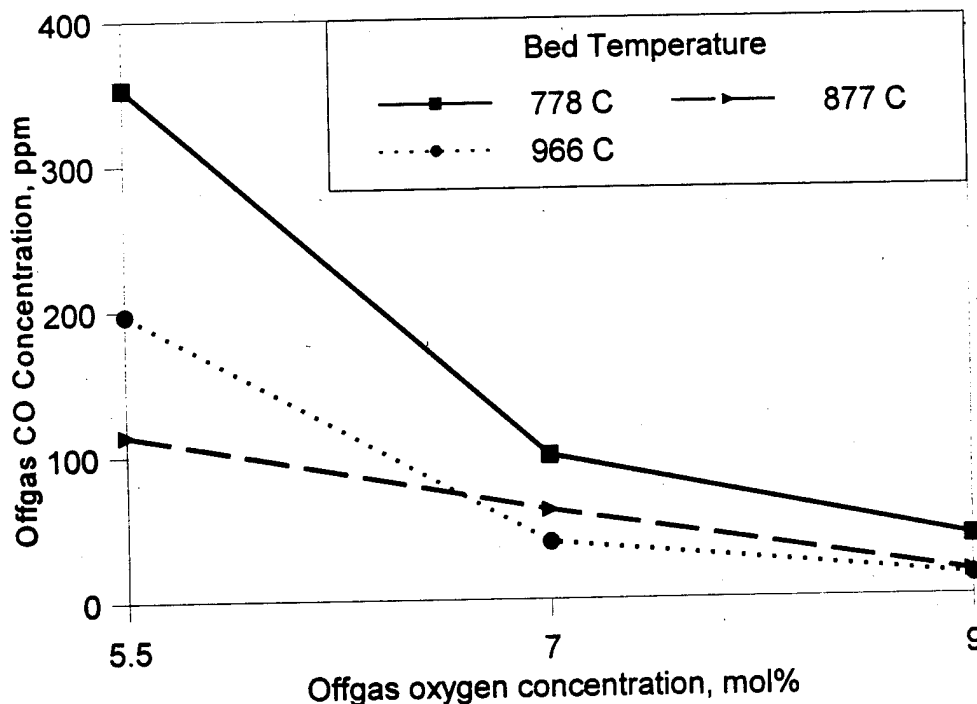


Figure 3. Offgas CO Versus Offgas Oxygen Concentration

C. STACK PERIODIC EMISSION SAMPLING

Stack sampling trains were used to measure the off-gas concentrations of volatile organics, semivolatile organics, dioxins and furans, particulates, metals, hydrogen chloride/chlorine (HCl/CL₂), and hydrogen cyanide (HCN).

Table 4 presents a summary of all stack sampling results for each test run. The results are listed as concentrations on a dry basis at standard conditions and corrected to 7 mole percent oxygen. The projected annual emissions from a full-scale process operating at a nominal capacity of 225 kg/h are presented in Table 5. The projected emissions were calculated by scaling up the emissions from the second day of testing (bed temperature of 870 °C), the most desirable condition for operation. The projected emissions are compared to current and potential regulatory limits.

1. Volatile and Semivolatile Organics

The five volatile organic compounds consistently detected by the sampling train were chloromethane, acrylonitrile, benzene, toluene, and styrene. These compounds were at relatively low concentrations throughout the sampling. The projected emissions of the volatile organics were several orders of magnitude less than the permitted values.

Table 4. Summary of Fluid Bed Reactor Continuous Emission Monitoring System (CEMS) Data

Test parameter	Day 1			Day 2			Day 3		
	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Stack Emissions									
Oxygen, mol.%	5.7	7.1	9.4	5.8	7.0	9.1	5.1	7.0	8.9
Carbon dioxide, mol.%	13.3	12.0	10.1	13.1	12.2	10.2	13.7	11.6	9.8
Carbon monoxide, ppm	353	99	41	114	61	16	197	39	14
Oxides of nitrogen, ppm	416	515	630	593	665	751	672	808	858
Sulfur dioxide, ppm	57	21	27	88	36	52	90	88	80
Total hydrocarbons, ppm	21	7	1.4	NM	NM	NM	9	4	0
Conversion, mass%									
Waste nitrogen to NO _x	NM	2.5	NM	NM	3.5	NM	NM	3.8	NM
Waste sulfur to SO ₂	NM	27.2	NM	NM	51.1	NM	NM	71.1	NM

NM = not measured

The most abundant semivolatile organic compound was bis(2-ethylhexyl)phthalate which is a common product of incomplete combustion when burning plastic materials. Other semivolatiles that were detected were phenol, naphthalene, and di-n-butylphthalate. The calculated emission of these compounds are several orders of magnitude below the permitted values.

2. Metals

The most abundant semivolatile organic compound was bis(2-ethylhexyl)phthalate which is a common product of incomplete combustion when burning plastic materials.

The metal emissions are a function of the concentrations in the waste feed and are typically present in the particulates and not the gases emitted during combustion. Three of the detected metals (arsenic, cadmium, and chromium) are considered carcinogenic. The projected emissions for these metals, as well as for lead and barium, were well below the allowable regulatory limits.

The system retention efficiencies of the cyclone and baghouse for the three carcinogenic metals averaged greater than 99.95 percent.

3. Particulates

The offgas concentrations of particulates averaged 18.2 mg/m^3 corrected to 7 mole percent oxygen in the off-gas. As shown in the table this is well below the current regulatory limit of 18.5 mg/m^3 imposed under 40 CFR 264, Subpart O. However, the EPA is currently considering lowering the particulate emission limit to 11.58 mg/m^3 . When evaluating the particulate emissions, it is important to keep in mind that the bags used in the pilot test were new. Over time, a dustcake forms on the inside of

4. Dioxins and Furans

The offgas concentrations of dioxins and furans ranged from 6.5 to 40.2 ng/m^3 or 0.14 to 0.64 ng/m^3 depending on whether they are expressed as dioxins and furans or expressed as tetrachlorodibenzo(para)dioxin (TCDD) equivalent [1].

Studies conducted by the EPA have shown that increased residence time of combustion offgases between 232 and 454°C correspond to increased emissions of dioxin and furans (USEPA, "Municipal and Waste Combustion Study: Combustion Control of Organic Emissions", EPA/530-SW-87-021C, NTIS Order No. PB87-206090). The Hazen pilot process was equipped with an uninsulated cyclone separator and water cooled heat exchanger. This equipment allowed the offgas to linger in the temperature range that is optimum for dioxin and furan formation. A full-scale process could be designed with an insulated cyclone to maintain offgas temperature above 454°C prior to entering a partial quench. The partial quench would rapidly cool the combustion gases to temperatures less than 232°C , reducing the residence time at the optimum temperature for dioxin and furan formation, and thus reducing the off-gas concentration of dioxins and furans below the regulatory limit [1].

The EPA regulatory standard associated with the emissions of dioxins and furans is the "6-nines Destruction and Removal Efficiency" imposed on facilities that process dioxin containing waste. This limit applies to dioxin containing wastes and not to plastic media blasting waste per se. Limits being considered are 5.4 to 9.7 ng/m^3 for total dioxin and furans and 0.12 to 0.17 ng/m^3 expressed as tetrachlorodibenzo (para) dioxin (TCDD) equivalents. Total (dioxin and furan) and TCDD equivalent data from the two test runs at the higher bed temperatures were within these anticipated limits. As already discussed, an appropriately designed full-scale process is likely to have lower emissions of dioxins and furans [1].

5. Hydrogen Chloride/Chlorine

Emissions of chlorides as HCl/Cl_2 averaged approximately 55 mg/m^3 (dry standard) or 4 g/h . The emissions for a full-scale process are projected to be 115 g/h , which is well below the current and potential regulatory limit [1].

Table 5. Comparison of Projected Full-Scale Emissions to Regulatory Limits (for 125 t/a)

Compound	Projected emissions	Curent regulatory limits		Potential regulatory limits	
		Value	Source	Value	Source
Volatile organics, g/h					
Chloromethane	0.041	NM		2333	BIF
Acrylonitrile	0.024	NM		125	BIF
Benzene	0.343	NM		1000	Utah
Toluene	0.017	NM		250000	BIF
Semivolatile organics, g/h					
Phenol	0.175	NM		25000	BIF
Napthalene	0.819	NM		83	BIF
Di-n-butylphthalate	0.004	NM		41667	Utah
bis(2-Ethylhexyl)phthalate	10.8	NM		13917	Utah
Metals, g/h					
Barium	0.07	41667	BIF	41667	BIF
Lead	0.068	75	BIF	75	BIF
Arsenic	0.001	1.9	BIF	1.9	BIF
Cadmium	0.121	4.7	BIF	4.7	BIF
Chromium	0.063	0.7	BIF	0.7	BIF
Miscellaneous emissions					
Particulate, µg/m³	18100	185300	RCRA	11600	CETRED
HCl/Cl₂, g/h	113.5	1816	RCRA	333	BIF
Cyanides, g/h	0.314	NM		16700	BIF
Total PCDD/PCDF, ng/m³	6.5	NM		5.4 - 9.7	CETRED
TCDD equivalent, ng/m³	0.12	NM		0.12 - 0.17	CETRED

NM = not measured; BIF = Boiler and Industrial Furnace regulations; Utah = State of Utah Air Toxics Policy; CETRED = Combustion Emission Technical Resource Document; TCDD = tetrachlorodibenzo (para)dioxin; PCDD = polychlorinated dibenzo-p-dioxins; PCDF = polychlorinated dibenzofurans; RCRA = Resource Conservation and Recovery Act

The estimated HCl/Cl₂ emission rate from a 227 kg/h full-scale unit based on the pilot test data is 0.1 kg/h. The current regulatory limit for emissions of HCl is less than 1.82 kg/h or greater than 99

percent removal. Therefore the pilot test data shows that the full-scale process would comply fully with the current regulatory limit for emissions of HCl [1].

the bags which reduces the particulate emissions. It is possible that the pilot test would have met the proposed new limits with conditioned bags. However, the present data indicates that a wet electrostatic precipitator may be required if the lower limits are imposed.

6. Hydrogen Cyanide

The nitrogen content of the organic plastic media provides the potential for generation of hydrogen cyanide (HCN). Combustion of plastics containing organic nitrogen may produce measurable quantities of HCN, particularly at temperatures below 760°C. The pilot test results indicate HCN was generated at all three test runs. The HCN emissions decreased with increasing bed temperature. The projected emissions of HCN for a full-scale unit, processing waste at 227 kg/h, are well below the allowable levels derived from the Reference Air Concentration from the Boiler and Industrial Furnace (BIF) regulations [1].

D. RESIDUAL ASH CHARACTERIZATION

The primary residues produced during the pilot test were the ash collected in the cyclone and in the baghouse. The majority of the ash (greater than 97 percent) was collected in the cyclone. Samples from the two sites were collected from each test and analyzed for particle size distribution, bulk density, and metals content.

A summary of the particle size distribution using a sieve analysis is presented in Table 6. The results indicate that the mean particle size of the cyclone ash (65 to 100 μm) appeared to be slightly less than the baghouse ash (135 to 170 μm). The fact that the baghouse ash particles were larger than those from the cyclone suggests that the particles in the baghouse agglomerated. The particle size analyses of the cyclone ash indicates bed medium carryover.

A summary of the metals analysis for the ash samples is shown in Table 7. The metals content of the untreated waste and the roasted ash from the pre-pilot test are included in the table for reference. The concentration of volatile metals such as mercury, cadmium, lead, potassium, and sodium, were higher in the baghouse ash than in the cyclone ash. This is attributed to the volatility of the metals.

The silicon content of the cyclone ash was higher than that of the starting waste feed, which confirms that there was bed carryover.

E. STABILIZATION TEST RESULTS

The PMB waste is considered RCRA characteristically hazardous waste because of the leachability of certain metals. These same metals remain in the ash, at now higher concentrations. The ash generated in the fluid bed reactor is classified as characteristically hazardous waste and must be managed accordingly.

Materials that are hazardous due to leachability of metals must be stabilized as required by 40 CFR 268 (Land Ban). An important objective of the pilot study was to determine whether the ash can be stabilized and meet the leachability requirements.

The stabilization requires additions of binding materials which increases the mass to be disposed. The stabilization tests were to determine the principle ability to stabilize. No optimization for either cost, mass or volume were undertaken.

Ash collected from the cyclone and baghouse from each test run were blended together to form a

representative composite sample for stabilization. This waste composite blend was analyzed according to the Toxicity Characteristic Leaching Procedure (TCLP) identify the baseline leachability of metals contained within the sample. Results from this test are presented in Table 7. The results show that the waste ash exceeds the allowable limit for cadmium and chromium.

The waste ash was mixed with various materials used to stabilize metals. These materials included Type II Portland cement, fly ash, and blast furnace slag. A total of six different mixtures were made and mixed with water to form a slurry. Each slurry was placed into a mold and allowed to cure for approximately eight days. After curing, each specimen was analyzed using the TCLP test.

Four of the six mixtures had leachability values below the regulatory limits. Three of these contained Type II Portland cement and ground blast furnace slag. The lowest bulking factor for a specimen passing the TCLP leaching criteria was approximately 1.8 grams of added mix per gram of ash.

Table 6. Ash Particle Size Distribution

Particle size (μm)	Cumulative mass percent passing through sieve	
	Cyclone sample	Baghouse sample
149	62.5	87.5
74	55.8	87.3
37	47.0	87.2
30	43.6	87.1
25	42.0	87.0
20	38.9	86.9
12	30.2	86.5
8	21.1	85.7
4	11.2	71.0
2	2.9	41.1
1.3	1.1	20.0
Mean particle size	55 - 60	2 - 3

Table 7. Summary of Ash Metal Analytical Results

Metal analyte	TCLP values (mg/l)							Regulatory limit
	Ash sample	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Sample #6	
Arsenic	< 0.20	< 0.29	< 0.29	< 0.58	< 0.58	< 0.58	< 0.58	5
Barium	0.8	1.2	1.2	1.2	2.6	2.2	1.8	100
Cadmium	288	140	< 0.025	0.03	< 0.025	< 0.025	< 0.025	1
Chromium	32.5	0.16	9.9	0.12	2.2	0.52	0.22	5
Lead	< 0.50	400	0.28	0.3	0.32	< 0.28	< 0.28	5
Mercury	0.0003	0	0	0	0	0	0	0.2
Selenium	< 0.03	< 0.50	< 0.36	< 0.71	< 0.71	< 0.71	< 0.50	5
Silver	< 0.03	< 0.36	< 0.50	< 0.50	< 0.50	< 0.50	< 0.50	1
Stabilization sample mixture components (mass %)								
Type II Portland cement	30	25	28.6	4.3	10	40		
Fly ash	0	5	7.1	0	0	0		
Blast furnace slag	0	0	0	38.5	90	360		
Sodium sulfide	0	0	7.1	0	0	0		
Water	41.5	41.5	48.4	42.1	60	147.5		

SECTION V LIFE CYCLE COST ANALYSIS

The cost-effectiveness of thermal treatment and disposal of PMB waste (thermal treatment option) was determined using life cycle cost (LCC) analysis. An LCC analysis was also performed for the existing off-site landfill disposal (direct landfill option) and compared against the thermal treatment option. The analyses assumes that the PMB waste will be treated on-site, and the ash will be transported off-site for stabilization and disposal. The disposal site (RCRA Subtitle C landfill) is considered to be the same for either option [3].

A. METHODOLOGY

The LCC analysis of the thermal treatment option includes the capital, operation, and maintenance costs of the fluidized bed reactor; the cost of transporting the residual ash to landfills; and finally the cost of treating and disposing of the residual ash. This assumes that the waste management facilities stabilize and dispose of residuals on-site and do not incur additional transportation costs. The quantity of ash to be disposed using this option may range from 4 to 68 mass percent of the waste, depending on the waste type. The LCC analysis of the landfill option includes only the costs of transportation, stabilization, and disposal of wastes.

The LCC was estimated using the net present value (NPV) methodology. Using the NPV methodology, the life cycle cash flows are discounted to the present and summed over the life of the equipment. The LCC was calculated in terms of total and per ton bases. Analyses were done in 1994 constant dollars and using the real discount rate as prescribed for cost-effectiveness, lease purchase, and related analyses by the Office of Management and Budget (OMB) [4].

A spreadsheet model was developed to perform the LCC analysis. Table 8 shows the model printout of the major input parameters and the values used in this analysis. Focus Environmental, Inc., provided the detailed cost data for a fluidized bed reactor with a 2174 ton per year design capacity (continuous operation). The original capital estimates for the fluidized bed reactor are based on the original capital estimates from Dorr-Oliver, Inc. The resulting cost breakdown is shown in Table 9. The miscellaneous costs include installation costs (foundations, structures, and equipment), taxes, and contingency. These costs are estimated as the sum of 2.8 times the process equipment capital cost and 0.2 times the instrumentation cost. The process equipment capital and miscellaneous costs will change with design capacities.

For other design capacities, the "six-tenths-factor rule" (economy of scale) was used for the capital cost estimation, while the appropriate linear economy of scale was assumed for the labor cost. Annual maintenance costs were assumed to be 3% of the total capital cost. Utility costs and material costs are presumed to be proportional to the amount of waste treated. The heating value of the waste was considered in the utility costs. The analyses were expressed in constant dollars using the real discount rate and the forecasted real cost escalation rates for different input parameters. The input parameters are based on government publications.

As was previously mentioned, the landfilling option is assumed to consist of two components. They are the waste transportation from the generation site to the landfill, and the treatment and disposal (T&D) of the waste at the landfill site. The total transportation cost is the sum of two components which are based on distance and ton-miles. The transportation cost is calculated using the following equation:

$$Y = (8.23 + 0.23X)Z, \quad [\$]$$

where Y is the transportation cost in 1994 dollars and X and Z are the total distance in miles and tons of waste transported, respectively.

Table 8. Major Parameters Used in LCC Analysis

Parameter	Amount
Residual ash content, mass%:	
B48	4.6
B50	67.5
B70	8.8
Selected mix (B48 + B70)	17.1
Number of shifts/day	1
Working time, d/y	250
Maintenance cost, %	3
Real discount rate, %	4.8
Equipment life, year	15
Landfilling cost, \$/ton*	235
Transportation distance, mi	200
Unit cost:	
Electricity, \$/kWh	0.07
Natural gas, \$/(Btu x 10 ⁶)	3.1
Process water, \$/(Gal x 10 ³)	0.5
Plant air, \$/(Scf x 10 ³)	0.65
Chemicals, \$/lb	200
Real cost escalation rate, %/y:	
Electricity	0.6
Natural gas	2.3
Process water	1.0
Plant air	1.0
Chemicals	1.1
Wages	1.2
Landfilling (transportation cost)	2.3
Labor Rate:	
Supervisor, \$/y	50000
Engineer, \$/y	40000
Operator, \$/y	30000
Material handling, \$/y	20000
Total overhead (direct + indirect), %	50
Utilities required per ton of waste:	
Electricity, kWh	494.3
Natural gas, Btu x 10 ⁶	4.8
Process water, Gal x 10 ³	1.3
Plant air, Scf x 10 ³	0.9
Materials required, ton/ton of waste	0.1

*A more realistic figure, recieved after completion of this report, is close to 1 \$/kg.

Table 9. Estimate of Capital Cost Breakdown

Capital item	Estimated cost
Process equipment capital	\$592K
Detailed design engineering	\$270K
Permitting, facility startup, and utility connections	\$640K
Instrumentation	\$310K
Miscellaneous	\$1705K
Total	\$3517K

The T&D costs are site-specific, dictated by the balance between the supply and the demand for landfills. The latest Environmental Information (EI) survey (Perket 1994) [5] indicates that in recent years (i.e., since 1991) landfill costs have decreased because of a reduced demand for hazardous waste services and the availability of larger, more economical landfills. This decline is attributed to new regulations which prohibit landfills from accepting certain hazardous wastes, and other regulatory initiatives which emphasize waste minimization and on-site treatment or containment. On the other hand, it is possible that future regulations may increase the demand for landfill disposal. In this analysis, we assumed that no major market changes will occur in the future. Therefore, the T&D costs increase only with inflation. The scenario of the T&D cost increasing in the future was considered by performing a sensitivity analysis.

The EI survey also indicated that hazardous waste landfill prices for bulk shipments of waste are less than for drummed shipments. Bulk shipments require less material handling and are about a third less expensive than drummed waste. The T&D cost (bulk quantities) is assumed to be \$235 per ton. This value is higher than the 1993 national average of \$170 per ton as reported in the EI survey [5].

At a multiwaste generating facility, the cost of waste separation is an important factor to be taken into consideration in the LCC analysis. For the direct landfill option, the waste will need to be separated before being transported to the disposal site. However, waste separation costs are currently unavailable, and are therefore considered only in the sensitivity analysis.

B. RESULTS

Table 10 lists the major base-case assumptions used in this analysis. Most of these assumptions are based on information applicable to Hill Air Force Base. Note that the annual waste-processing rate of 500 tons/year is much higher than the current rate of 120 tons/year. The cost-effectiveness of the treatment option is evaluated in terms of the total LCC and the LCC per ton of waste treated. Seven variables (annual waste processing rate, residual ash content, equipment life, separation cost, escalation rate, transportation distance, and T&D cost) are considered to be the most sensitive to the total LCC. These sensitivity analyses were performed by varying each parameter individually while the other parameters were held constant at their base-case values. These parameters are listed in Table 10.

Detailed analyses were performed to compare the cost-effectiveness of the thermal treatment option to existing landfill option in terms of transportation cost (i.e., distance) and the T&D cost. Break-even analyses were performed for four different annual waste generation rates in order to estimate the combined effects of distance and the treatment and storage cost (however, the latest disposal cost

figures, which are about four times larger than those considered in this analysis, are not included).

1. Base-Case Results

Figure 4 shows the breakdown of the estimated total LCC of the thermal treatment (1 shift/day and 3 shifts/day) and the direct landfill options under the assumptions listed in Table 10. The total LCC of the thermal treatment option is estimated to be \$6.36M compared to a estimate of \$1.57M for the direct landfill option (the latest available figure is about \$6 M). The LCCs per ton for the treatment and direct landfill options are estimated to be \$848 per ton and \$209 per ton, respectively. The thermal treatment option has the lower landfilling cost (i.e., \$1.3M) because T&D is proportional to the reduction of waste mass due to treatment. The capital cost contributes more than 50% of the total LCC for the thermal treatment option. The costs for materials and landfilling (i.e., transportation, treatment, and disposal) are a small fraction of the total cost. The utility costs shown in Figure 5 are mainly electricity, natural gas, process water, and plant air.

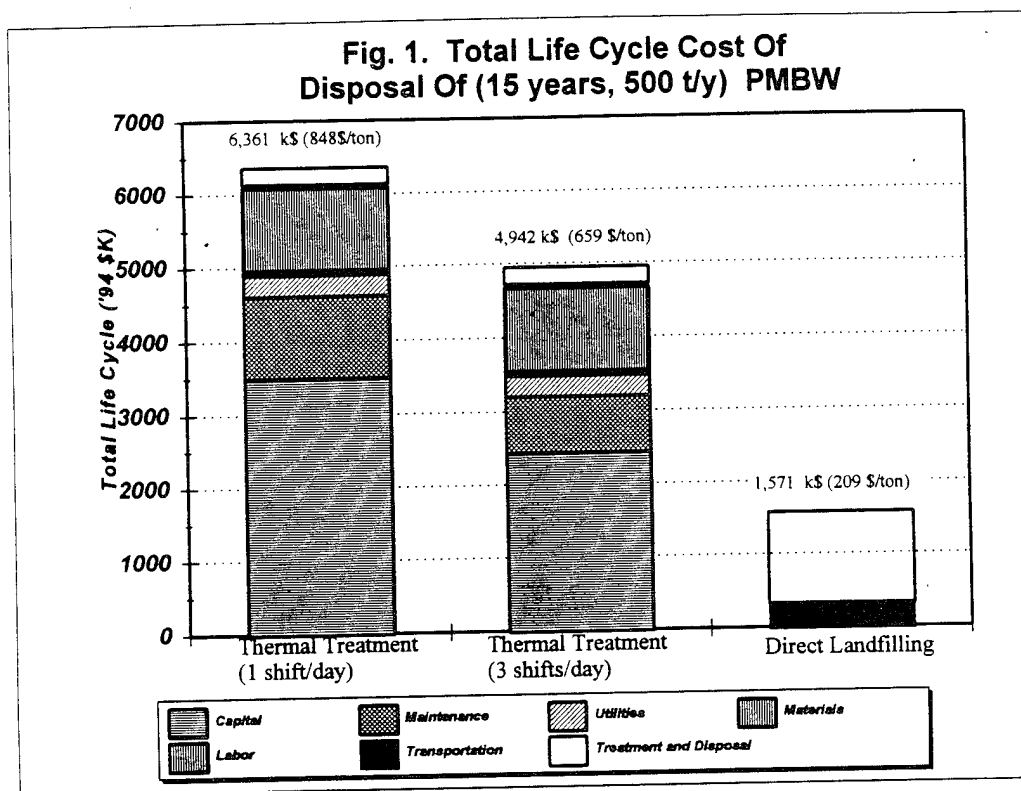


Figure 4. Total LCC for Thermal Treatment and Direct Landfill Options

Table 10. Base Case Assumptions for LCC Analysis

Parameter	Assumption
Waste processing rate	500 ton/y
Residual ash content	17.1 mass %
Equipment life	15 y
Treatment and disposal (T&D) cost	\$235/ton*
Real T&D cost escalation rate	0% per year
Waste separation cost	\$0.0/lb
Transportation distance	200 miles
Real discount rate	4.8 %
Number of shifts per day	1
Working time	250 days

*Latest estimates are about four times higher.

A smaller system with a better operating factor can be employed by operating three shifts per day for the same annual waste processing rate. Lower capital and maintenance costs associated with a three shift/day operation will reduce the total LCC by \$1.42M (compared with the 1 shift/day operation). The LCC per ton for a three shift/day operation is \$189 less than for a one shift/day operation; yet this cost is three times greater than for the direct landfill option (this value is lower than the latest estimate for landfill use).

2. Sensitivity to the Annual Waste Processing Rate

The sensitivity of the total LCC for the thermal treatment option to the annual waste processing rate is shown in Figure 5. The annual waste-processing rate determines the design capacity of the thermal treatment system. The total LCC increases from \$4.7M to \$9.6M as the rate increases from 200 tons/year to 1000 tons/year. The LCC per ton decreases due to the economies of scale from \$1528 to \$641 for a similar change in the waste-processing rate. Beyond the capacity of 400 tons/year, the LCC per ton decreases less rapidly and levels off beyond 800 tons/year capacity. Under the given base-case assumptions, the thermal treatment option may not be cost-effective even for processing rates of 1000 tons/year (the most recent values are four times higher).

3. Sensitivity to Residual Ash Content

The residual ash content of the waste is an important factor in determining the cost-effectiveness of the thermal treatment option. The lower the ash content, the lower the landfill cost for the thermal treatment option. The ash content depends on the type (B48, B49, and B50) of waste stream processed and may vary from 5 to 68 mass percent. The sensitivity of LCC to the residual ash content is shown in Figure 6. Total LCC as well as the cost per ton increases linearly with the increase in residual ash content. Total LCC increases from \$6.2M to \$7M as the ash content increases from 10 mass percent to 60 mass percent. The LCC per ton increases from \$833 to \$938 for a similar increase in the ash content. For an ash content of 5 mass percent, the estimated LCC per ton for the thermal treatment

option is \$823 per ton, compared to \$209 per ton for the direct landfill option.

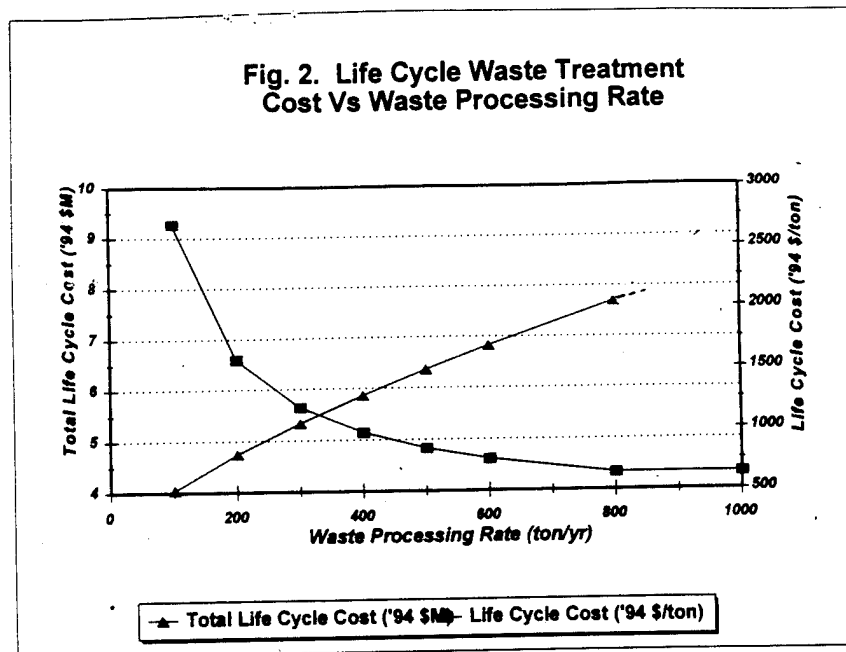


Figure 5. Life Cycle Waste Treatment Cost Versus Waste Processing Rate

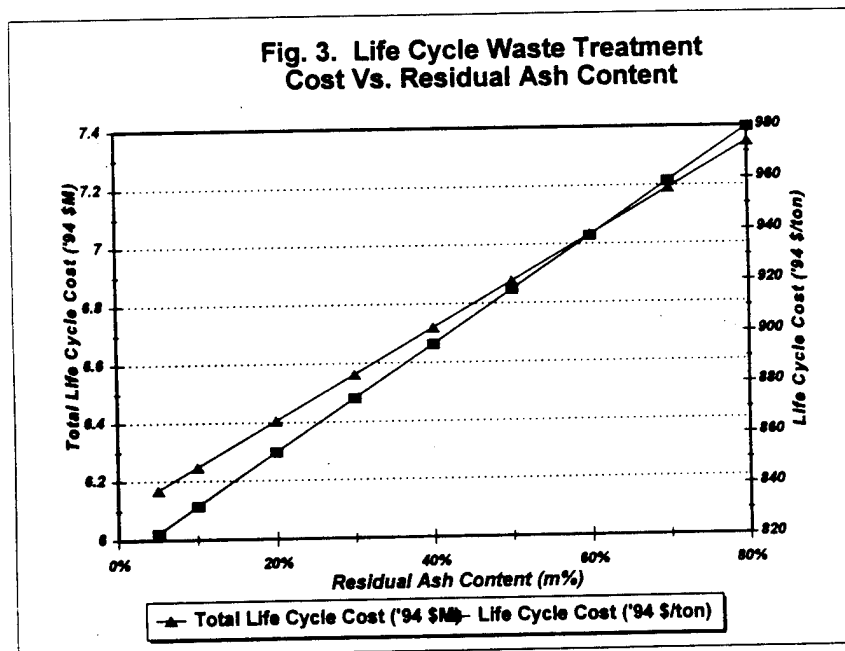


Figure 6. Life Cycle Waste Treatment Cost Versus Residual Ash Content

4. Sensitivity to Equipment Life

Figure 7 shows the LCC of the thermal treatment option using different values for life of the thermal treatment system. The LCC is sensitive to the life of the treatment system, since its initial capital cost amortized by the total quantities of waste processed during the system lifetime. The total LCC increases from \$5.6M to \$7.0M as more quantities of wastes are processed with the increase in the equipment life from 10 to 20 years. The LCC per ton decreases from \$1120 to \$699 for a similar increase. The reduction in the LCC per ton with the increase in the equipment life becomes smaller when the life expectancy exceeds 16 years. This is because the LCC is present value discounted.

5. Sensitivity to the Waste Separation Cost

Figure 8 shows the total LCC for the direct landfill option as a function of the separation cost. The total LCC increases linearly from \$1.6M or (\$210/ton) for zero separation cost to \$13M or (\$1730/ton) for a separation cost of \$450/ton (\$0.45/kg). For waste separation costs exceeding \$190/ton (\$0.19/kg), which corresponds to an LLC of \$900/ton, the thermal treatment option becomes cost-effective compared to the direct landfill option.

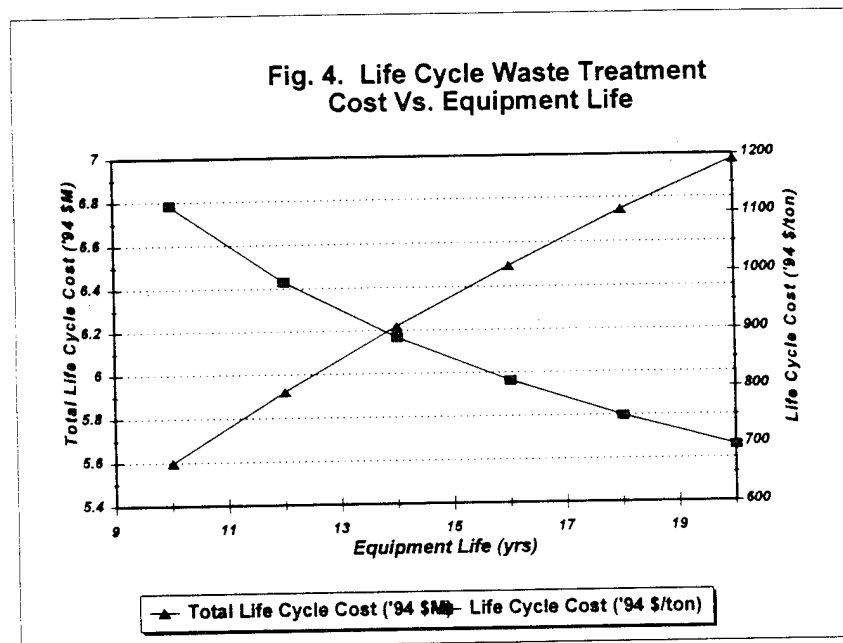


Figure 7. Life Cycle Waste Treatment Cost Versus Equipment Life

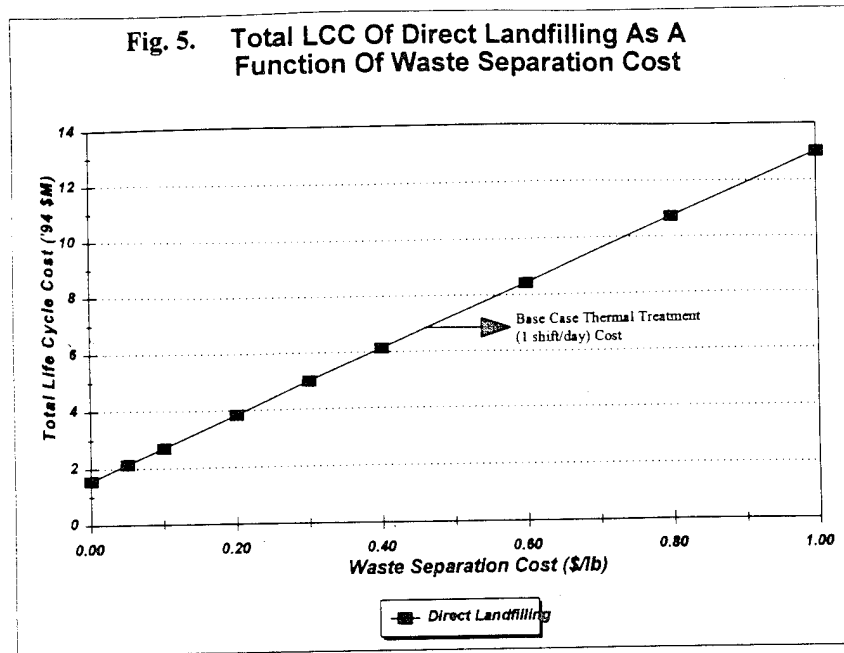


Figure 8. Life Cycle Waste Treatment Cost Versus Waste Separation Cost

6. Sensitivity to the Landfilling Cost

The landfilling cost is comprised of the transportation costs and the T&D costs. The T&D cost is site-specific. This necessitated using a range of T&D costs when determining the cost-effectiveness of the thermal treatment option. Figure 9 shows the total LCC for the thermal treatment and direct landfill options as a function of T&D cost. The total LCCs of the two options increase linearly (\$900 per unit for thermal treatment versus \$5255 per unit for direct landfill). The cost sensitivity is smaller for the thermal treatment option because less waste is landfilled (the residual ash content is assumed to be 17.1 mass percent). With an increase in the T&D cost, the LCC difference between the two options becomes smaller. At a crossover point, the thermal treatment option becomes more effective.

The transportation cost is assumed to depend on the quantity of waste and the transportation distance. This cost contributes to a smaller portion (approximately 22%) of the total landfilling cost. The total LCC of the two options as a function of distance is shown in Figure 10. The total LCCs for the two options increase linearly (\$243/mile for thermal treatment and \$1429/mile for direct landfilling). The difference in sensitivity is due to the difference in the quantity of waste to be landfilled.

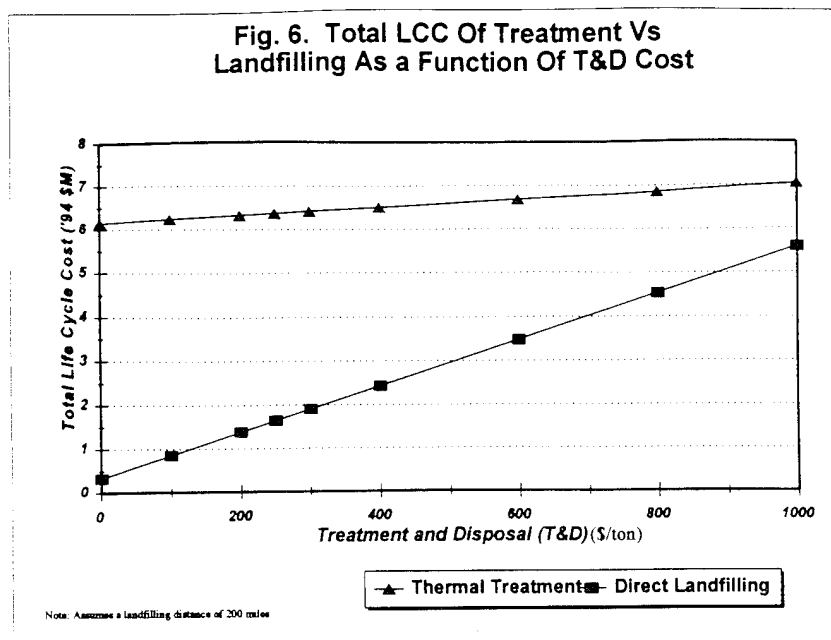


Figure 9. Total LCC as a Function of T&D Cost

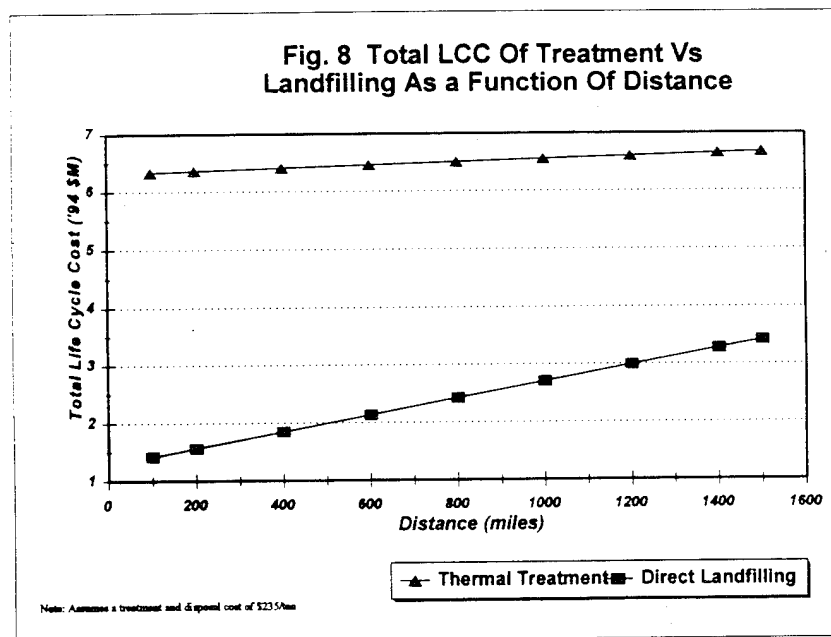


Figure 10. Total LCC as a Function of Transportation Distance

6. Break-even Analyses

The transportation distance and the T&D cost are site-specific. As demonstrated in Figure 6, the cost-effectiveness of the thermal treatment option depends on waste-processing rate. Therefore, the amount of waste processing, when combined with the transportation distance and T&D cost, determines the cost-effectiveness of a disposal option for a particular waste-generating facility. Break-even analyses were performed to determine the cost-effectiveness of four different annual waste-processing rates using different combinations of transportation distance and T&D costs.

Table 11 shows the break-even T&D cost as a function of transportation distance for several waste-processing rates. The table shows the T&D cost for the thermal treatment option to be cost-effective. For a T&D cost range of \$600 to \$1000 per ton, annual waste-processing rates of 750 to 1000 tons/year would be cost-effective. For example, if the transportation distance is 400 miles, then the T&D costs of \$965 and \$924 per ton would be cost-effective for waste-processing rates of 750 and 1000 tons/year, respectively. These costs can be lower (\$639 and \$598 per ton, respectively) if the transportation distance were 1600 miles instead of 400 miles.

The break-even transportation distance as a function of the T&D cost for different annual waste-processing rates of the thermal treatment option is shown in Table 12. The transportation distance would have to be unrealistically large (3000 to 7500 miles) for smaller waste-processing rates (250 to 500 tons/year) to be cost-effective. At higher waste-processing rates (750 to 1000 tons/year), a short transportation distance combined with higher T&D costs can make the thermal treatment option cost-effective. For example, and 750- to 1000-ton/year processing rate combined with a T&D cost of \$900 to \$1000 per ton would require a short transportation distance (less than 640 miles) for the thermal treatment option to be cost-effective. For a T&D cost of \$900 per ton, the necessary transportation distances are 640 to 487 miles for waste-processing rates of 750 and 1000 tons/year, respectively.

Table 11. Break-even T&D Cost as a Function of Transportation Distance

Transportation distance		Waste generation rate (ton per year)			
		250	500	750	1000
km	miles				
320	200	\$2195	\$1335	\$1020	\$978
640	400	2140	1281	965	924
970	600	2086	1227	911	869
1290	800	2032	1172	857	815
1610	1000	1977	1118	802	761
1930	1200	1923	1063	748	706
2250	1400	1868	1009	693	652
2580	1600	1814	955	639	598

Table 12. Break-even Transportation Distance as a Function of T&D Cost

Treatment and disposal cost (\$/ton)	Waste generation rate (ton/year)			
	250	500	750	1000
200	7540 miles	4377 miles	3216 miles	3063 miles
30	7172	4009	2848	2695
40	6804	3641	2480	2327
500	6436	3273	2112	1959
600	6068	2905	1744	1591
700	5700	2537	1376	1223
800	5332	2169	1008	855
900	4964	1801	640	487
1000	4596	1433	272	119
1100	4228	1066	0	0
1200	3860	698	0	0
1300	3492	330	0	0
1400	3124	0	0	0

C. CONCLUSIONS

The cost-effectiveness of the thermal treatment option for the disposal of PMB waste is compared with the direct landfilling option using a life cycle cost analysis. Under base-case assumptions, most of which are appropriate for Hill Air Force Base, the estimated total LCCs of the thermal treatment and the direct landfilling options are \$6.4M (\$848/ton) and \$1.6M (\$205/ton), respectively. The cost savings, associated with reducing the volume of the waste by thermal treatment, are considered large enough to be more favorable than direct landfilling in some cases. The high LCC for the thermal treatment option is due to capital and maintenance costs associated with the fluid bed reactor. A smaller thermal treatment system with a better operating factor reduces the total LCC to \$4.9M (\$659/ton).

LCC analyses indicate that thermal treatment is economically feasible for high waste-processing rates and a combination of high T&D cost coupled with low transportation distances (and vice versa). For Hill Air Force Base, where the waste generation rate is low (120 tons per year), thermal treatment is not considered cost-effective [3], if the cost of direct landfilling remains low.

The cost of separating the waste at the generation site is an important factor to consider when determining the cost-effectiveness of thermal treatment. Under base-case assumptions, the thermal treatment option becomes cost-effective with the direct landfill option when the separation costs exceed \$0.19/kg. The multiwaste processing capability associated with the thermal treatment option may make this option much more cost-effective than direct landfilling.

SECTION VI ENVIRONMENTAL IMPACT ANALYSIS

A review was performed to identify and evaluate potential environmental impacts associated with an onsite fluidized bed thermal treatment process and for direct landfilling. The review revealed advantages and disadvantages for each alternative.

A. DIRECT LANDFILLING

While not always the disposal method of choice, proper landfilling can be viewed as a controlled method of waste disposal. Waste can be consolidated during landfilling and its impacts to the environment can be monitored and evaluated. Air dispersal and leaching of contaminants are relatively low. Proper management practices during operation, proper closure, and adequate post-closure monitoring reduces impacts to human health and the environment. Personnel training and the use of protective equipment reduce worker exposure. Excursions, resulting from design modifications, can be accommodated by leachate collection and treatment systems.

A proposed landfill is approximately 300 km (200 miles) from Hill Air Force Base. This would keep transportation-related impacts low. The landfill appears to have the capacity to properly dispose of the PMB waste for the foreseeable future. If the volume of wastes generated were to increase significantly, then the generation rates may exceed landfill disposal capacity. This would effectively render landfilling nonviable. Such a scenario could occur if Hill Air Force Base were to become a regional or national center for aircraft maintenance. Waste volume increases resulting from transporting wastes from other locations to Hill Air Force Base for disposition is likely to be an environmentally undesirable practice. Increased transportation and atmospheric emissions are two of the most obvious impacts that would need to be assessed.

B. FLUIDIZED BED THERMAL TREATMENT

Fluid bed thermal processing can be used to reduce the mass or volume of the PMB waste. However, this process also disperses some combustion gases and particulates to the environment. The regulatory climate for thermal treatment emissions is becoming increasingly restrictive and is expected to continue to do so. Thermal treatment of PMB wastes is discouraged by some, and the practice may soon be prohibited, because of the generation of hazardous decomposition products. Thermal treatment of PMB waste emits minute quantities hazardous materials from the paint to the air, and creates dioxins and furans from the plastic medium. Emissions from the pilot study are well below regulatory limits, those limits may change. It is also possible that production-scale emissions may differ from those in the pilot study, although it is unlikely that they will exceed regulatory limits.

Alternative Air Quality Standards (NAAQS) criteria pollutants of concern are lead, NO_x , and ozone. Preliminary analysis of the pilot test data using the EPA screening model SCREEN 2 (1991) suggests no exceedances of the NAAQS for NO_x would occur as a result of fluid bed thermal treatment. However, Davis County is in moderate nonattainment of the NAAQS for ozone. It is likely that a fluid bed reactor located in Davis County would receive close scrutiny. Beryllium emissions would also need to be evaluated. Other constituents in the emissions appear to be below accepted levels of concern [1].

Significant waste volume reduction (85% or better) is achieved through fluid bed thermal treatment. The hazardous constituents are concentrated in the remaining ash. To be accepted in a permitted hazardous waste disposal facility, the ash is stabilized (Toxicity Characteristic Leaching Procedure test positive) prior to landfilling. This requires some additional handling and increases the potential for personnel exposure and additional air dispersion. Mitigative measures could reduce this potential. Because of the amount of plastics contained in PMB wastes, appreciable amounts of dioxins/furans can be generated during treatment. A maximum stack-gas concentration for total dioxins and furans of 30 ng per dry standard cubic meter (adjusted to 7% oxygen) is given for municipal waste combustors in 40 CFR

60.53a. This concentration was exceeded in one of the pilot test runs (Run #1).

More stringent concentration limits may be imposed for stacks of facilities other than municipal waste combustors. A fluid bed reactor may distribute some of the hazardous constituents (metals) to the land surface in a populace area of the state. Emissions would enter the atmosphere from a 9 meter stack at 18 m/s. Because of the meteorological conditions in the region, metals would be redistributed on the ground and available for plant, animal, and human uptake. The relatively arid climate would also increase the amount of time for the metals to be leached by precipitation. The long and short-term environmental impacts of metals distribution and accumulation under these conditions are considerations that impact the licensing of the facility.

SECTION VII DESIGN AND OPERATIONAL CONSIDERATIONS

A. WASTE PROFILE

The PMB wastes generated at Hill Air Force Base, and at other facilities, are currently (1994) being disposed of by stabilization and landfilling at a cost of 1.08 \$/kg (980\$/ton). A cost/benefit evaluation of the proposed fluid bed thermal treatment process shows the impact of the profile (i.e. quantity and characteristics) of the PMB waste. The pilot tests demonstrated that a fluid bed treatment process is an efficient process to reduce the volume of PMB waste for disposal. However, waste streams such as the B50 stream from Hill Air Force Base would leave significant residue after combustion that requires additional management [1].

Based on the 1993 waste profile generated at Hill Air Force Base, 125 metric tons of PMB waste would have resulted in approximately 21 metric tons of ash residue requiring stabilization and management (17 metric tons from the B50 waste stream and 4 metric tons from all other waste streams). Therefore a better definition of the waste profile and summary of current waste management practices and costs is essential for conducting an effective cost/ benefit evaluation.

B. OPERATING FACTOR

The actual throughput of a full-scale fluid bed combustion process compared to the design capacity is the operating or capacity factor. The suggested (by HAFB) operating schedule was one shift a day, five days per week for the full-scale process. This translates into an operating factor of 0.24 (assuming maintenance can be conducted on the off shifts). The same facility operating continuously (24 hours per day, 7 days per week) has an operating factor of approximately 0.85 (assuming 0.15 for maintenance and miscellaneous downtime) and can process 3.5 times, more waste. The economy of the facility improves by processing the waste by approximately a factor of 2.

C. METAL RECYCLE

Since the ash residues contain high concentrations of cadmium and lead, recycle for metal recovery is considered an alternative for plain disposal. Metal recycling facilities (three random companies) have minimum limits for concentrations of specific metals in the wastes. One company had a minimum feed metal concentration low enough to accept the ash from the fluid bed combustion process for recycle. The cost for the recycling process was estimated at \$200 per drum or \$500 per metric ton delivered in bulk.

D. LIFE CYCLE COST

Design considerations are important in assessing the life cycle cost of operating a fluid bed reactor thermal treatment process. This is because most of the total cost is due to capital equipment and maintenance expenditures. The LCC analysis performed for the thermal treatment process indicates high processing rates make this option cost-effective when compared to direct landfilling. In order to be more cost-effective, the capital equipment should be capable of handling high waste-processing rates and require as little maintenance as possible.

E. ENVIRONMENTAL IMPACT

There are environmental concerns associated with both thermal treatment and direct landfilling options. The fluid bed reactor is technically an incinerator, and is therefore subject to stringent emission regulations by the EPA. The pilot-scale test indicated that this process can meet the current and potential regulatory limits for emissions. However, this may not be perceived as a preferred waste-treatment process. A fluid bed reactor must be designed with the most efficient emission collection system possible in order to meet the most stringent regulations.

SECTION VIII CONCLUSIONS AND RECOMMENDATIONS

The pilot test demonstrated that the volume of solid PMB waste, such as generated at Hill Air Force Base can be reduced by as much as a factor of 20 by treatment in a fluid bed reactor. During the pilot test operation, the reactor met the emission regulatory standards associated with the gaseous combustion products. The ash residue formed during combustion can be stabilized to meet regulatory standards for leachability by encapsulating the ash in a solid cement-slag waste form.

The life cycle cost analysis indicates that the fluid bed reactor thermal treatment process can be cost-effective in some cases when compared to direct landfilling, even though capital and maintenance costs are relatively high. Several environmental concerns exist with thermal treatment of PMB wastes. These concerns require further investigation to license a fluid bed reactor thermal treatment process.

This study, and the data of the engineering scale test, provide the basis for determining whether thermal treatment of PMB waste to reduce the volume of solids to be disposed should be built. The economic evaluation uses input data available at the time of the study (1994) and ancillary environmental impact information. As mentioned in the report, after completion of the study, but prior to publishing this report, additional information became available. This information shows that direct landfilling costs have already increased significantly relative to the cost assumed in the study. These new costs are on the order of 1\$/kg vs previously 0.25 \$/kg, which are within, or even exceed, the range of cost calculated for the thermal treatment.

SECTION IX
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APPENDIX

PILOT TEST REPORT FOR FLUID BED INCINERATION OF PLASTIC MEDIA BLASTING WASTES

SUBMITTED TO:

MARTIN MARIETTA ENERGY SYSTEMS
OAK RIDGE, TN

January 1995
Focus Project No. 029407

PREPARED BY:

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1.0 EXECUTIVE SUMMARY

Martin Marietta Energy Systems (MMES), acting under its Contract Number DE-AC05-84OR21400 with the Department of Energy (DOE), is investigating methods to reduce the volume of hazardous wastes generated by plastic media blasting (PMB) to remove paint from military aircraft. In an earlier project, bench-scale testing was conducted using rotary kiln thermal treatment technology in order to demonstrate PMB waste volume reduction and to determine the fate of metals contained in the PMB waste. A summary of the bench-scale testing objectives, methodologies, and results is presented in the report entitled "Test Report for Bench-Scale Testing of a Thermal Treatment System for Wastes from Plastic Media Paint Stripping Operations" (Bench-Scale Test Report) prepared by Focus Environmental Inc. and dated January 1994. The bench-scale testing showed that the PMB waste became tacky and foamed during heating.

MMES issued a Request for Proposal (RFP) on February 14, 1994 to potential bidders to conduct pilot-scale treatability studies of commercially available thermal treatment processes for treating the plastic media/paint waste (PMB waste) streams. Focus Environmental, Inc. (Focus) submitted a proposal (Proposal Number 029407) and was awarded a contract for performing pilot testing using fluidized bed oxidation on a continuous basis for achieving volume reduction of the PMB waste. A cyclone separator followed by cooling and fabric filtration (baghouse) was used to remove ash, bed carryover, and regulated metals from the combustion offgas.

A survey of the PMB waste generated at Hill Air Force Base (HAFB) was conducted to determine the most representative sample for pilot testing. The two largest PMB waste streams generated at HAFB are denoted as B48 and B70 wastes. The B48 stream contains Type II plastic media. The B70 stream contains Type V plastic media. Samples of these two waste streams were obtained from HAFB and composited to form a representative sample for pilot testing. The composite waste sample was analyzed for elemental analysis, heat content, particle size distribution, and total metals. The pilot-scale testing of the FBR was conducted during a three day period in September 1994.

The waste composite sample was processed in the pilot scale fluid bed reactor (FBR) while varying bed temperature and offgas oxygen concentration. Process operating data and emission sampling was conducted at the varying conditions. Emissions of carbon monoxide (CO), total hydrocarbons (THC), oxides of nitrogen (NO_x), and sulfur dioxide (SO₂) were measured as a function of bed temperature and offgas oxygen concentration. Emissions of particulate, metals, volatile organics, semivolatile organics, dioxins and furans, hydrogen chloride/chlorine, and hydrogen cyanide were measured in the offgas as a function of bed temperature.

Grab samples of the bed media and ash captured in the cyclone separator and the baghouse during the pilot test were characterized. These residuals were analyzed for particle size distribution, bulk density, and total metals. The ash captured in the cyclone separator and baghouse from all three days of testing was composited to form a sample for stabilization testing. The ash composite

sample was mixed with varying quantities of fly ash, blast furnace slag, Type II Portland cement, and water to determine if the ash could be stabilized to meet the applicable regulatory standards for leachability.

In addition to the B48 and B70 waste streams, HAFB generates another significant waste stream that contains a mixture of the plastic blasting media and inert material. This waste stream is called B50 waste. A sample of this waste stream was also obtained from HAFB for characterization.

The pilot test demonstrated that fluid bed combustion technology could effectively reduce the volume of PMB wastes while maintaining emissions at levels that could meet current and anticipated regulatory standards. Results and conclusions from the pilot testing include:

The annual mass of PMB waste generated at Hill Air Force Base (HAFB) is approximately 123 metric tons (142 tons).

The Type II plastic blasting media has a significant organic nitrogen content (approximately 21 mass percent).

The B48 and B70 PMB waste streams have ash contents of approximately 2.5 and 6.7 mass percent, respectively.

The B50 waste stream contains inert material (garnet and ash) at a concentration of approximately 65 mass percent.

A bed fluidizing air velocity of approximately 0.75 m/s (2.5 ft/s) was determined to be optimum using silica as a bed media. A fluidizing velocity of 0.85 m/s was used successfully in the pilot tests with silica as the bed media.

The combined residence time for the combustion gas in the fluid bed and freeboard should be a minimum of 3.5 seconds.

Total ash recovery was approximately 81 mass percent. The remainder of the ash was retained in the bed by agglomerating to the bed media. Use of a bed modifier (Kaolin clay) will be required to minimize agglomeration of the ash to the bed media.

The cyclone particulate removal efficiency was approximately 97 weight percent.

At a bed fluidizing velocity of 0.85 m/s, approximately 20 mass percent of the ash captured in the cyclone and baghouse was a result of bed media carryover.

The average particle size of the bed media increased during the pilot test runs due to agglomeration of the bed media with ash residues from the waste.

Concentrations of phosphorus, sodium and potassium in the bed media increased much more rapidly than other metals compared to the feed rates of these metals to the system. This also indicates agglomeration of the bed media.

Offgas concentrations of carbon monoxide and total hydrocarbons decreased with increasing bed temperature at constant offgas oxygen concentrations. Offgas concentrations of carbon monoxide and total hydrocarbons decreased with increasing offgas oxygen concentrations at constant bed temperatures.

Offgas concentrations of NO_x increased with increasing bed temperature at constant offgas oxygen concentrations. Offgas concentrations of NO_x increased with increasing offgas oxygen concentrations at constant bed temperatures. Concentrations of NO_x in the offgas ranged from 416 to 858 ppm by volume.

Conversion of organic nitrogen to NO_x averaged approximately 3.3 mass percent.

Offgas concentrations of SO_2 typically increased with increasing bed temperature at a constant offgas oxygen concentration. Offgas concentrations of SO_2 typically decreased with increasing offgas oxygen concentrations at a constant bed temperature. Offgas concentrations of SO_2 ranged from 21 to 90 ppm by volume.

Detectable emissions of hydrogen cyanide were measured during all three pilot test runs. The offgas concentration of hydrogen cyanide decreased with increasing bed temperature.

Fluid bed combustion processes burning PMB waste should be operated at bed temperatures between 800 and 900°C and offgas oxygen concentrations greater than 9 percent by volume to minimize emissions.

The concentration of cadmium in the baghouse dust increased with increasing bed temperature. As a result, the corresponding emissions of cadmium in the offgas from the baghouse also increased.

The lowest stack concentration of total tetra through octa dioxins and furans was 6.5 ng/m³ measured at a bed temperature of 877°C and an offgas oxygen concentration of 7 volume percent. The corresponding tetrachlorodibenzo(a)para)dioxin (TCDD) toxic equivalent emission rate was 0.12 ng/m³. These measurements are on a dry basis at 1 atmosphere and 20°C, corrected to 7 volume percent oxygen. These values are essentially equal to proposed regulatory limits that may be applied to a future full-scale system (EPA Combustion Emission Technology Resource Document, CETRED). Modifications to the full-scale process design compared to the pilot scale process should decrease the offgas concentrations of dioxins and furans below those measured in the pilot test.

Concentrations of particulate in the offgas averaged 18,200 Mg/m³ (0.0079 grains per dry standard cubic foot) corrected to 7 volume percent oxygen. This value is an order of magnitude less than the current regulatory limit and essentially equal to the proposed regulatory limit that may be applied to the future full-scale process (CETRED). Conditioning of the bags and development of a dust cake on the bags should decrease the particulate emissions from a full-scale process compared to the pilot test.

System removal efficiencies for metals were greater than 99.9 mass percent for those metals which were present at concentrations greater than 100 mg/kg in the starting waste. This indicates that a full-scale process equipped with a baghouse will be able to meet the metal emission standards.

Concentrations of cadmium and lead were significantly higher in the baghouse dust than in the cyclone ash during the pilot test. This data indicates these two metals have higher volatility than other metals.

The ash residue can be stabilized to meet the regulatory standards for leachability using mixtures of ash, Type II Portland cement and blast furnace slag.

2.0 PROJECT DESCRIPTION

2.1 INTRODUCTION

Martin Marietta Energy Systems (Energy Systems), acting under its Contract No. DE-AC05-84OR21400 with the Department of Energy, is investigating methods to reduce the volume of hazardous wastes generated by plastic media blasting to remove paint from military aircraft. The waste to be treated consists of mixtures of Type II and Type V spent plastic blasting media and paint flakes. The waste is a RCRA characteristic hazardous waste because of the leachability of chromium and cadmium. The physical form of the waste is a fine powder with a particle size typically between 38 and 300 Mm (400 and 48 mesh). Energy Systems has contracted with Focus Environmental, Inc. (Focus) to conduct a pilot-scale treatability study using commercially available thermal treatment process components for treating the plastic media/paint waste streams.

The major findings of previously completed bench-scale treatability testing included:

The mass of waste can be reduced by a factor of approximately 100 using thermal processing to volatilize the organic media present in the waste

The temperature at which the waste blend began to melt was between 250 to 310°C (482 to 590°F)

Significant organic vapor release begins at approximately 325°C (617°F)

The melted waste blend has a significant viscosity and expands into a foam upon the liberation of organic vapors (the expansion ratio is between 8:1 to 10:1)

The melted waste displayed a tendency to "stick" to the surface of the thermal test unit.

The results of the bench-scale test were used to plan a pilot-scale test for evaluating the feasibility of thermally processing the waste. Fluid bed thermal oxidation technology was proposed for evaluation in the pilot-scale testing. This document describes the pilot-scale testing and presents the results of the tests.

2.2 OBJECTIVES

The overall objectives of the testing includes (1) demonstrate the feasibility of using fluid bed reactor (FBR) technology and associated air pollution control system (APCS) to achieve sufficient waste volume reduction at the selected waste feed rates while operating at process conditions which minimize the emissions of criteria air pollutants and (2) provide sufficient data and information necessary to scale-up the process from the pilot-scale to a full-scale design. Specific objectives of the pilot-scale test include:

Characterize the waste feed including the explosive characteristics of the PMB waste dust in air mixtures

Demonstrate an adequate waste feed system configuration for introducing the waste into the FBR

Identify material for use as the solid fluidizing media

Evaluate the effect of bed temperature and excess oxygen on selected emissions from the process

Establish target process operating conditions (i.e., fluidizing velocity, bed operating temperature, and excess oxygen) that provide effective fluid bed oxidation while minimizing selected emissions

Determine process-specific information (i.e., bed carryover, ash carryover, bed cooling requirements, baghouse pulse frequency) under the various test conditions

Determine characteristics of the ash generated by the process

Determine the ability to stabilize a composite ash sample from the process.

2.3 BASIC APPROACH

Focus chose Hazen Research, Inc. (Hazen) of Golden, Colorado as the subcontractor to conduct the pilot-scale test. Hazen conducted the pilot-scale test utilizing a continuous process consisting of a FBR and dry APCS (cyclone separator, dry quench, and baghouse). A continuous emissions monitoring system (CEMS) was used to analyze the process offgas for selected components. The process offgas was sampled for particulates, metals, volatiles, semivolatiles, dioxins/furans, HCl/Cl₂, and cyanide using stack gas sampling trains. A detailed description of the test apparatus, test protocol, and emission sampling is presented in Section 4.0.

The starting waste feed material and process-generated residues were analyzed for metals and used with measured waste flow rates and ash generation rates to determine the fate of the metals during thermal processing. Data and observations were collected to determine the effectiveness of the processing scheme to vaporize and thermally destruct the organics from the waste while minimizing specific process offgas emissions (NO_x, SO₂, CO, THC, volatiles, metals, semivolatiles, dioxin/furans, and cyanides).

Hazen conducted the tests using existing equipment. Hazen and selected analytical subcontractors analyzed the samples generated during testing for all parameters of interest. Focus and Energy Systems personnel present during the three days of test runs included:

Paul Sadler (Focus)
Greg Smith (Focus)
David Lloyd (Energy Systems)
Uri Gat (Energy Systems).

3.0 PRE-PILOT TEST ACTIVITIES

3.1 WASTE PREPARATION AND CHARACTERIZATION

3.1.1 Waste Description

Selection of a representative waste sample for testing is critical to the generation of test data that can be used for scale-up of operating and emission data. One of the major generators of the PMB waste is Hill Air Force Base (HAFB) in Davis County, Utah. To insure that the sample selected for testing was representative of the majority of the waste to be processed, Focus contacted HAFB personnel responsible for various areas at the facility where plastic media blasting (PMB) wastes are generated. Notes from these contacts are included in the Annexes.

HAFB uses various types of media to strip paint from metal surfaces, primarily aircraft. The various types of stripping media may be broadly categorized as plastic or inert (garnet or silica). The actual media used for a specific purpose may be a specific plastic media or a blend of plastic and inert media, depending on the application. There are five specific types of plastic media that may be used at HAFB. These five types include:

- Type I - Polyester (thermoset)
- Type II - Urea Formaldehyde
- Type III - Melamine Formaldehyde
- Type IV - Phenol Formaldehyde (thermoset)
- Type V - Acrylic (thermoplastic).

Of these five types, Type II and V are the types used most frequently at HAFB. The majority of the spent blasting media at HAFB is categorized in one of four different waste streams. These waste streams include:

- B48 Waste - Type II plastic blasting media only
- B49 Waste - Type II plastic blasting media combined with garnet or silica. The mixture typically consists of less than 10 percent garnet or silica by mass.
- B50 Waste - Type II plastic blasting media combined with garnet. The mixture typically consists of 50 to 80 percent garnet by mass.
- B70 Waste - Type V blasting media only.

Table 3-1 presents a summary of the PMB waste generation data for these four waste streams for calendar year 1993. According to the generators, each PMB waste stream is likely to include some trash (i.e., plastic bags, cigarette butts, felt paper, tape, glue, safety wires, etc.).

The B48 and B70 wastes consist only of paint chips and the plastic blasting media. These two waste streams accounted for approximately 40 and 28 mass percent of the total PMB wastes generated in 1993, respectively.

The B49 and B50 waste streams are blends of Type II plastic and inert materials. The B49 waste streams contain varying concentrations of inert materials but are predominantly Type II plastic blasting media (less than 10 percent inert materials). The B50 waste stream contains garnet at concentrations ranging from 50 to 80 percent. The garnet fraction of the B50 waste stream is not combustible and would present a significant ash loading to a fluid bed combustion system. The data in Table 3-1 indicates that the B49 and B50 waste streams accounted for 13 and 20 mass percent of the total PMB wastes generated in 1993, respectively.

3.1.2 Waste Sample Preparation

Based on the survey results listed in Table 3-1, five samples of PMB waste material were collected and shipped from HAFB. These samples included:

- B48 Waste, Site Number N03B (142 kg)
- B48 Waste, Site Number N04A (113 kg)
- B70 Classifier Waste, Site Number LA30 (111 kg)
- B70 Baghouse Waste, Site Number LA30 (112 kg)
- B50 Waste, Site Number K06H (38 kg).

Each individual sample was blended and an aliquot was taken for measurement of particle size distribution. The two B48 samples were combined and blended as were the two B70 samples. Aliquots of the two blended samples were taken for elemental analysis. The balance of these two samples was combined and blended to form a B70/B48 composite PMB waste sample for testing. The resulting composite sample consisted of 46 mass percent B70 waste and 54 mass percent B48 waste. Aliquots of the waste composite sample were taken and analyzed for particle size distribution and elemental analysis.

The B50 waste sample was blended and maintained as a separate sample. An aliquot of the B50 waste was taken and analyzed for particle size distribution, elemental analysis, heat content and total metals.

A flow chart showing the sample handling and blending of the B70 and B48 is presented in the Annexes.

3.1.3 B70/B48 Waste Characterization

Table 3-2 presents the results of particle size distribution analyses of the individual PMB waste samples that were blended to form the waste composite sample. The particle size distribution for the PMB waste composite sample is also presented. The results indicate that the B48 waste has a smaller mean particle size than the B70 waste.

Table 3-3 presents the results of the elemental analysis of the various PMB waste samples. The B48 waste has a significantly higher nitrogen content than the B70 waste. This was expected due to the nitrogen component of the urea formaldehyde in the Type II plastic. The B48 waste had a higher moisture content likely due to the smaller particle size as shown in Table 3-2. Both waste samples have a significant heat content. The B70 waste has a significantly higher carbon, hydrogen, and heat content than the B48 waste. The results for the composite waste sample are consistent with the blend proportions of the individual samples. The nitrogen content will contribute to the potential formation of nitrogen oxides (NO_x) in the fluid bed combustion process.

Table 3-4 presents the results of metals analyses conducted on the waste composite sample. An aliquot of the waste composite sample was taken and ashed in a muffle furnace to remove the organic content. The resulting ash was also analyzed for total metals. The results of the ash analyses are also presented in Table 3-4. The RCRA metals cadmium, chromium, barium and lead were present in significant concentrations in the waste composite sample. Other components present in significant concentrations that may impact the fluid bed operation include potassium and sodium.

After ashing, the resulting metals analyses were consistent with the starting metals analyses considering the 96 percent volume reduction upon ashing. The ash analysis also indicated a significant sulfate content and a detectable concentration of phosphorus. The presence of these parameters could have implications for the fluid bed media when operated for an extended period of time.

The fusion temperature was also assayed for the ash from the B70/B48 composite. The data showed that in an oxidizing atmosphere, the ash began melting at a temperature of about $1,275^{\circ}\text{C}$ ($2,327^{\circ}\text{F}$) and became fluid at a temperature of $1,385^{\circ}\text{C}$ ($2,525^{\circ}\text{F}$). These temperatures are significantly higher than the planned operating temperature of the fluid bed reactor (FBR). Therefore, melting of the ash from the B70 and B48 wastes is not expected to be a concern.

A thermogravimetric analysis (TGA) was conducted on the waste composite sample to measure the sample mass loss as a function of temperature and to determine the temperature range at which the organic components would evolve. A copy of the resulting thermogram is presented in Appendix A. The results show that a significant mass loss occurred between 250 and 600°C (482 and 316°F) resulting in a final product that was equivalent to approximately 4.5 percent of the starting mass. The final ash content corresponds closely with that determined in the ultimate analyses (4.01 mass percent) and from the percent ash determined by muffle furnace roasting of the composite sample (4.23 mass percent).

Differential thermal analysis (DTA) provides a graphic display of exothermic and endothermic reactions of a sample as a function of temperature. A DTA was performed on the muffle furnace roasted ash from the waste composite sample to determine whether phase changes, eutectics, or melting would occur within the temperature range of the planned fluid-bed tests. No significant reactions of this type were recorded, and the final sample from the test was a loose powder, similar in nature to the starting sample. A copy of the results of the DTA is presented in the Annexes.

3.1.4 Explosive Characteristics

An aliquot of the waste composite sample was taken and evaluated to determine the explosive characteristics of the waste dust in air. The results of these tests are summarized in Table 3-5. The results indicate that under certain conditions it is possible for waste dust and air mixtures to explode. The maximum pressure developed during the test (7.7 bar) indicates that all containment vessels where dust clouds of the waste material could form should be grounded and fitted with an explosion relief vent. However, any explosion resulting from handling the waste material can be classified as a weak explosion meaning that the rate of pressure rise would be relatively low compared to explosive dust clouds of other materials (for example, aluminum dust). Therefore, the size of the relief vent can be relatively small. Sizing of the relief vents would be conducted during detailed process design.

The test results indicate that the waste powder is relatively insensitive to electrostatic charges such that there is no need for operators to wear antistatic footwear or to forbid contact of the dust cloud with plastic materials. However, the pneumatic transfer line to the FBR should be made of a conductive, grounded material.

Most dust clouds require a minimum concentration of oxygen in the dust cloud for an explosion to occur. Dust clouds classified as exhibiting severe explosion potential usually have a minimum explosive oxygen concentration of approximately 8 volume percent (i.e., if the oxygen concentration is less than this value, an explosion will not occur). Nitrogen purging may be used in some systems to decrease the oxygen concentration to a level less than the minimum explosive concentration. However, this can be very expensive, especially in "open systems" where the nitrogen blanket is constantly having to be replenished. The minimum oxygen concentration required for an explosion to occur with the PMB waste dust cloud is relatively high (15 volume percent). Therefore, nitrogen purging to reduce the oxygen concentration from ambient (21 volume percent) to 15 volume percent may be cost effective.

3.1.5 B50 Waste Characterization

Tables 3-3 and 3-4 also present the results of analyses conducted on the sample of B50 waste. The results verify the significantly higher ash content expected from this waste due to the inorganic garnet present in the waste. The heat content of the B50 waste (8,702 kJ/kg) is much lower than the heat content of the B48 or B70 wastes (15,747 to 25,005 kJ/kg) because of the dilutional effect of the

inert garnet. Metals analyses indicate lead and chromium concentrations are at levels similar to those found in the other wastes. However, the cadmium concentration is much lower (85 mg/kg compared to 985 mg/kg). The garnet content is reflected in the increased silicon content of the B50 waste. The concentrations of iron and aluminum are also higher in the B50 waste, most likely a result of blasting paint from steel or aluminum surfaces.

Tabular results of all analyses reported by Hazen are included in Appendix A.

3.2 BED MEDIA SELECTION AND CHARACTERIZATION

Various materials have been used as bed media in fluid bed combustion processes. Two of the more commonly used media are silica (20 by 65 mesh) and alumina (32 by 65 mesh). Silica is often used because it is readily available and inexpensive. Alumina may be considered when there is a possibility of silica interacting with the ash from the processed material to form eutectics, which results in ash sticking or melting. The following is a description of testing and results conducted to determine which of these two media to use in the pilot scale fluid bed test.

Cold flow fluidization tests were performed on the silica and alumina to determine the gas flow necessary for optimum fluidization. Tests were conducted in a laboratory-scale glass fluidization system, including a glass fluid-bed vessel 10.2 cm (4 inches) in diameter by 61.0 cm (24 inches) tall. The system is equipped with a cyclone and baghouse for capture of fine particles that may escape the fluid-bed vessel.

The results of the fluidization study on these samples showed that optimum fluidization characteristics were obtained at an air velocity of approximately 0.76 m/s (2.5 ft/s) and 0.61 m/s (2.0 ft/s) for the silica and alumina, respectively. Optimum determinations were made based on visual observation of the fluidization characteristics. Carryover of the bed media was 0.03 mass percent for the silica media and 5.5 mass percent for the alumina.

The higher gas velocity for optimum fluidization of the silica media means that more fluidizing air could be used, which allows more oxygen in the system for combustion, resulting in higher feed capacities. Also, if silica media is used, the lower carryover minimizes the quantity of makeup bed media that will have to be added to the system. Low carryover also minimizes the quantity of residue that has to be handled by the air pollution control system and the cost of subsequent disposal of that residue.

A cold flow fluidization test was also conducted on ash from a muffle furnace roasted sample of the B50 waste to determine the fluidizing characteristics of the B50 ash. The results of this test allowed evaluation of the potential for the ash from the B50 waste to be used as the bed media. The fluidizing velocity of the B50 ash was 0.11 m/s (0.36 ft/s) which is significantly lower than the fluidizing

velocity for either the silica or alumina media. Operation of the fluid bed such that the ash from the B50 waste would remain in the FBR to form the bed would severely limit the capacity of the unit.

DTAs were performed using varying mixtures of the waste plastic ash and silica media. The purpose of these tests was to determine whether the mixture of waste ash with silica would result in any undesirable reactions that caused eutectic formation. A DTA of the silica media was conducted as a baseline. These analyses show no reactions of significance, other than the silica phase change that was expected to occur at a temperature of about 570°C (1,058°F). These results gave preliminary indications that the waste ash and silica would not interact detrimentally and were used as the other criteria for selecting silica as the fluidizing medium. Graphical presentations of the DTA results from silica media and ash mixtures are included in the Annexes.

As a result of these tests, silica was selected as the fluidizing medium for the pilot scale fluid bed tests.

4.0 PILOT-SCALE TEST DESCRIPTION AND EXECUTION

4.1 EQUIPMENT DESCRIPTION

Figure 4-1 illustrates a process flow diagram of the HAZEN pilot-scale waste processor. The HAZEN pilot-scale process consists of five major systems: (1) waste feed system, (2) fluid bed reactor (FBR) system, (3) air pollution control system, and (4) process monitoring systems. All devices are constructed of materials designed to withstand the conditions expected during normal operation.

4.1.1 Waste Feed System

A 0.03 m³ (1 ft³) storage hopper was used for storage of the waste feed material. Waste material was discharged via a rotary valve to a constant-speed screw feeder. The screw feeder was equipped with a 5 cm (2 inch) diameter screw that was used to transfer the waste material from the discharge of the rotary valve to a 1.3 cm (0.5 inch) diameter transport line. Compressed air from a blower passed through the transport line and conveyed the waste material to the FBR through a waste injection nozzle. Since the FBR was operated under a positive pressure, backflow through the screw feeder and hopper was prevented by a rotary valve at the base of the hopper. Waste feed rate was controlled by varying the rotational speed of the rotary valve. The waste feed rate was measured by monitoring the weight change of the hopper per unit time.

The waste injection nozzle consisted of two concentric nozzles. The pneumatically conveyed waste flowed through the inner nozzle. The conveying air served to distribute the waste feed across the entire cross-section of the FBR and to promote lateral mixing of the waste and solid fluidization media in the FBR. Cooling water flowed through the outer nozzle to indirectly cool the nozzle and prevent melting of the plastic waste material prior to entering the FBR. Some additional cooling was achieved via the air used to convey the waste material.

4.1.2 Fluid Bed Reactor

The FBR was used to thermally destroy the organic portion of the waste material. The entire waste combustion system was lined with 11.4 cm (4.5 inches) of high temperature castable refractory backed by 11.4 cm (4.5 inches) of insulating castable refractory. The FBR itself has three sections joined together by flanges; (1) windbox, (2) fluidized bed, and (3) freeboard.

The windbox is an L-shaped housing used to provide sufficient residence time to preheat ambient air, which was then used to preheat the solid fluidizing media in the FBR. A 0.32 GJ/h (300,000 Btu/h) propane burner is attached to the front of the windbox and is capable of preheating the FBR up to an operating temperature of 1,000°C (1,850°F). Two air streams were supplied to the windbox. One air stream supplied combustion air necessary to operate the burner while a second air stream was used for fluidization.

The waste material had a high heat content and thus was capable of sustaining the FBR at the desired operating temperature during normal operation without preheating the fluidizing air. The windbox burner was used only during startup to raise the FBR to the specified operating temperatures.

The fluidized bed contained 159 kg (350 lb) of solid fluidization media (bed media) that was heated to combustion temperatures. The base of the fluidized bed has a perforated plate equipped with 14 T-bar tuyeres for equal distribution of the fluidizing air across the base of the bed. The fluidized bed is 38 cm (15 inches) inside diameter extending to a height of 152 cm (60 inches).

Waste was fed continuously to the fluidized bed through a port located 15 cm (6 inches) above the base of the fluidized bed.

The freeboard zone is designed to provide additional residence time for completion of combustion and to minimize carryover of solid fluidizing media in the offgases exiting the FBR. The lower section of the freeboard zone is a tapered section, 33 cm (13 inches) long that serves as a transition zone from the fluidized bed. The upper section of the freeboard zone has a 53 cm (21 inch) inside diameter and is 58 cm (23 inches) tall. The increased diameter of the upper section results in a reduced gas velocity, which in turn causes the particles to disengage from the combustion gases. The volume in the freeboard section also provides more residence time for completion of combustion. The top of the freeboard section has a 10 cm (4 inch) inside diameter pipe used to duct the exiting combustion gases to the air pollution control system (APCS).

4.1.3 Air Pollution Control System

The APCS consists of a cyclone separator, dry quench, baghouse, induced draft fan, and stack.

A 20 cm (8 inch) diameter cyclone separator is used to remove coarse particulates from the combustion gas exiting the FBR. Coarse particulates are discharged via gravity into a totally enclosed ash collection canister. The combustion gas exits the cyclone separator and enters the dry quench.

The dry quench consists of three indirect heat exchangers in series used to lower the temperature of the combustion gas exiting the cyclone separator to temperatures acceptable for baghouse operation. To maintain the integrity of the bags, the heat exchangers were operated such that the combustion gas temperature was lowered to less than 260°C (500°F). Potable water was used as the heat exchange medium in a countercurrent flow pattern to the combustion gases. The water exiting the first heat exchanger was sent to drain. The quenched combustion gas exited the dry quench to the baghouse.

The baghouse was used as a final particulate removal device. The baghouse contained a total of 16 bags fabricated from fiberglass felt. Each bag was 11.4 cm (4.5 inches) in diameter and 91.4 cm (36 inches) long. The fiberglass felt bags have a maximum operating temperature of 260°C

(500°F). Pulsed air was used to discharge collected dust from the bags as required. A manually-operated rotary air-lock valve was used to discharge collected particulates from the baghouse hopper to an ash collection canister.

An I.D. fan was used to maintain the APCS under negative pressure and to transport the cleaned combustion gas from the process. The I.D. fan is a fixed speed fan with a damper valve used to control the draft created by the fan. The fluidizing air blower at the front of the FBR acts as a forced draft fan and provides pressure to lift the bed media for fluidization. Therefore, the pressure at the entrance to the process was positive and the pressure at the end of the process was negative. The pressure balance point (i.e., the point in the process where the pressure equals the atmospheric pressure) was near the outlet of the freeboard section.

4.1.4 Process Monitoring System

A list of the process monitoring instruments used during the pilot test is summarized in Table 4-1. Figure 4-2 shows the locations of the specific monitors listed in Table 4-1.

Two Type "K" thermocouples were used to monitor temperature in the windbox. Pressure in the windbox was measured using a single pressure gauge. Calibrated orifice meters were used to measure the feed rates of fluidization air.

Type "K" thermocouples were used to monitor temperature in the fluidized bed. With the base of the fluidized bed as the point of reference, three thermocouples placed 120° apart are located at a height of 15 cm (6 inches), one thermocouple is located at a height of 31 cm (12 inches), and three thermocouples placed 120° apart are located at a height of 46 cm (18 inches). A single thermocouple is also located at heights of 61, 76, and 92 cm (24, 30, and 36 inches) above the base. Two Type "K" thermocouples were used to measure temperature in the freeboard zone. The pressure drop across the entire FBR was measured via a differential pressure gauge.

Pressure drop across the cyclone separator was measured by a differential pressure gauge. The flowrate of water to the heat exchangers was measured manually using a rotameter. Two Type-K thermocouples were used to measure the heat exchanger inlet and outlet gas temperatures.

Pressure drop across the baghouse was measured using a differential pressure gauge. Two Type "K" thermocouples were used to measure temperature of the gases entering and exiting the baghouse.

The combustion gas was continuously sampled at the outlet of the baghouse and analyzed for O₂, CO₂, CO, SO₂, THC, and NO_x. A heat-traced line was used to transport the combustion gas sample to the CEMS. The sample first passed through a heated 2 - Mm filter. The dust-free sample was cooled rapidly to approximately 2°C (35.6°F) to condense and remove water from the gas sample. Specific gas analyzers utilized include:

Infrared Industries Model 2200 analyzer for O₂
Infrared Industries Model 703 analyzer for CO₂
Beckman Model 864 analyzer for CO
ThermoElectron Model 40 analyzer for SO₂
Beckman Model 951A analyzer for NO_x
Thermo Environmental Instruments Model 51 analyzer for THC.

Critical monitoring devices were calibrated prior to conducting the pilot testing. Records of calibrations conducted are included in the Annexes.

4.1.5 Process Monitoring and Control Center

The pilot-scale facility is equipped with on-line instrumentation to obtain process operating data. Process temperatures and gas composition data were monitored and recorded continuously. A data acquisition system was used to monitor and record selected process data. A multipoint recorder was used to record temperatures continuously.

4.1.6 Stack Sampling Equipment

Stack sampling trains were used to take samples for determination of the following emissions:

Particulates and metals (Multiple Metals Sampling Train, MMT, 40 CFR 266)
Volatiles Organic Sampling Train (EPA Method 0030, VOST, SW-846)
Semivolatiles and dioxin/furans (EPA Method 0010, M0010, SW-846)
HCl/Cl₂ and hydrogen cyanide (Modified EPA Method 0050, MM5, 40 CFR 266).

Schematic diagrams of the sampling trains used during the testing are provided in Appendix E.

4.2 TEST EXECUTION

4.2.1 Shakedown Testing

Prior to performing the three planned test runs, two days of shakedown testing were conducted. The purpose of the shakedown testing was to evaluate the operational ability of the system to meet the program objectives.

The first day of shakedown testing was conducted primarily to monitor the equipment operability and to provide the operators with process familiarization. The operators also became familiar with their respective responsibilities, and gained an understanding of how the system responded to the waste material being processed. Operators were familiarized with the feed characteristics,

required sample handling techniques, and fluidization characteristics, and data collection and process monitoring requirements specific to the testing.

The second day of shakedown testing was used to refine the operational procedures and fine tune the process in preparation for meeting the test parameters planned for the three scheduled test runs.

4.2.2 Matrix of Test Parameters

The pilot-scale test program developed for this study allowed for three (3) days of testing (one test run per day). The process was operated for approximately twelve (12) hours each day and shutdown overnight between test runs. The twelve hours of operations included startup, operation, shutdown, and sampling.

The key test parameters investigated during this pilot test included:

Bed temperature
Offgas oxygen concentration.

The target bed operating temperatures were 760, 870, and 980°C (1,400, 1,600, and 1,800°F), while the target offgas oxygen concentrations were 5.5, 7.0 and 9.0 volume percent for each target bed operating temperature. The pilot process was operated at the three target offgas oxygen concentrations for each bed operating temperature. The target bed operating temperatures span the range of typical fluid bed reactor operating temperatures. Cooling of the bed using water addition was required due to the high heat content of the waste feed.

The effect of varying the bed temperature and offgas oxygen concentration on process emissions was measured during the pilot test. Specific emissions measured included:

Carbon monoxide (CO), sulfur dioxide (SO₂), nitrous oxide (NO_x), total hydrocarbons (THC), metals, particulates, volatile organics, semivolatile organics, dioxins and furans, HCl/Cl₂, and hydrogen cyanide (HCN) as a function of bed temperature at an offgas oxygen concentration of 7.0 volume percent.

CO, SO₂, NO_x, THC as a function of offgas oxygen concentration at the three different bed temperatures.

4.2.3 Test Protocol

After completion of the shakedown test runs, the matrix of test parameters were demonstrated using the following protocol:

The FBR bed media provides a significant thermal mass such that waste feed can be initiated each morning after the process has been shut down overnight. The fluidization air was set at a predetermined rate based on the appropriate fluidization velocity determined from the cold flow fluidization tests. The waste feed was initiated and the rate adjusted to provide an oxygen concentration in the offgas of approximately 5.5 volume percent. The bed cooling water rate was adjusted to control the bed temperature at the desired set point. Once steady state has been achieved, the system will be allowed to run for at least one hour to record offgas concentrations of specific parameters at the test conditions.

After data was collected at the lowest offgas oxygen concentration, the waste feed rate was decreased while the fluidizing air rate remained constant. The waste feed rate was decreased until the offgas oxygen concentration was approximately 7.0 volume percent. The cooling water feed rate to the bed was decreased as required to maintain a constant bed temperature. The process was allowed to stabilize at these conditions for approximately 30 minutes. After the process had stabilized, offgas emission sampling was initiated. Samples were taken for total metals, HCl/Cl₂/HCN, volatile organics, semivolatile organics, and dioxin/furans. Sampling was performed at the baghouse outlet, near the location where gas was sampled to the CEMS. The sampling procedures follow the guidelines of EPA Method 0030 for volatiles (SW846, Third Edition, November 1986) and Method 0010 for semivolatiles, dioxins, and furans (SW846, Third Edition, November 1986).

Once the emission sampling requirements were completed, the waste feed rate was further reduced until the offgas oxygen concentration was approximately 9.0 volume percent. The cooling water feed rate was again reduced to maintain a constant bed temperature. The process was allowed to stabilize at the new conditions for approximately 30 minutes and then operate for a minimum of one hour to collect data regarding selected offgas concentrations.

At the end of the test run, a composite sample of the bed media was taken by collecting grab samples from the bottom and top of the bed and combining together. The bed sample taken each day was analyzed for particle size distribution, bulk density and total metals.

After the bed sample was taken, the waste feed, cooling water and fluidizing air were discontinued. The large, hot mass of bed media cooled slowly overnight so that the system could be quickly started up the next morning. The bed temperature dropped approximately 160°C (320°F) overnight.

Test products collected during all runs were weighed and saved as individual samples. Selected samples, or composites of selected samples were identified for analysis.

This protocol was repeated three times at the three test bed temperatures. When the final test was complete and the bed had cooled down to a temperature that allowed the bed material to be safely handled, the bed was removed, blended and a sample taken and analyzed for particle size distribution, bulk density and total metals.

5.0 PILOT TEST RESULTS

5.1 PROCESS OPERATING DATA

Pressures, temperatures and flow rates were measured during the pilot testing as indicated in Table 4-1. The resulting data were evaluated to determine average values for each parameter of interest for each test case. The resulting average values for process parameters associated with each test case are summarized in Table 5-1. Photographs of the process equipment and lab notes associated with operation of the pilot system are included in the Annexes.

5.1.1 Waste Feed Rates and Thermal Duty

The average waste feed rate to the FBR during the testing was approximately 10 kg/h (22 lb/h) corresponding to an average thermal duty of approximately 0.21 GJ/h (200,000 Btu/h). The residence time of the combustion gas in the FBR was approximately 3.5 seconds in all nine test cases.

There were no significant problems associated with the pneumatic transfer of the waste material into the FBR. The discharge from the screw feeder into the transfer line plugged once on the last day of testing. The plug was caused by a large paint chip. The full scale process will have a much larger transfer line. Therefore, plugging by large paint chips is expected to be of little concern. The waste to air ratio in the transfer line during the testing was 3.3 kg waste per kg of air or 3.7 kg of waste per m³ of air (0.23 lb waste per ft³ air).

5.1.2 Bed Velocity

The bed inlet gas velocity (calculated at bed temperature and bed inlet pressure) was maintained at approximately 0.85 m/s (2.8 ft/s) in the first two days of test runs. The bed inlet velocity was increased to approximately 0.98 m/s (3.3 ft/s) on the final day of testing. Both of these values are higher than the optimum fluidization velocity (0.76 m/s) measured during the cold flow fluidization study for the silica bed media as described in Section 3.2.

No problems were experienced during the first two days of operation, however, during the third day of operation, visible grains of bed media were observed in the cyclone ash. Carryover of the bed media indicates the bed velocity was excessive during the third day of testing. Therefore, if a similar silica media is used in the full scale process, the process should be operated at a bed velocity of approximately 0.85 m/s (2.8 ft/s).

5.1.3 Bed Temperature

Bed temperatures were measured at several locations as noted in Section 4.0. All thermocouples measuring bed temperature were indicating very similar temperatures during the first two days of testing indicating effective fluidization. Approximately half-way through the last day of testing,

the temperatures being measured in the bed began to slowly diverge. A possible cause is bed agglomeration resulting in a decrease in effective fluidization.

5.1.4 Baghouse Operation

One of the purposes of the testing was to measure the effect of bed temperature on the emissions of metals from the process. The primary process component for controlling metals emissions was a baghouse equipped with fiberglass felt (Hyglas) bags. Metal emissions from a baghouse can be impacted by changes in gas temperature at the inlet to the baghouse. The impact on metal emissions is caused by changes in metal volatility with changes in temperature (i.e., increased temperature will increase volatility). Therefore the temperature of the combustion gas entering the baghouse was controlled at a relatively constant value of 184°C (363°F) during the testing. This temperature is representative of typical baghouse operation.

In addition, the air-to-cloth ratio across the baghouse was maintained at approximately 0.5 m/min (1.6 ft/min). Baghouses are typically operated at air-to-cloth ratios of 0.3 to 1.5 m/min (1 to 5 ft/min).

The baghouse pressure drop never increased significantly due to a relatively low dust loading in the offgas stream. The baghouse did not require pulsing during each day of operation. The baghouse was pulsed at the end of each day to collect a sample of baghouse dust that had been collected. This indicates that a similarly designed and operated system may only have to be pulsed at the end of each day of operation. If a waste with a higher ash content (i.e., B50 waste) is processed, the ash loading would increase and baghouse pulsing may be required on a more frequent basis.

5.1.5 Ash Recovery

Table 5-2 presents a summary of the ash recoveries measured during the testing. The mass of ash fed to the process during each test was calculated by multiplying the ash concentration in the waste feed (4.01 mass percent) by the total mass of waste material fed during the test. Ash recoveries were in excess of 100 percent based on comparing the total mass of ash recovered from the cyclone and baghouse to the calculated mass of ash in the waste feed. Ash recoveries in excess of 100 percent are a result of bed carryover.

A silicon balance was conducted on the cyclone ash by comparing the silicon compositions of the cyclone ash and the ash from muffle roasting of the composite waste sample. The estimated bed carryover from the silicon balance confirmed the visible increase in bed carryover noted in the third day of testing.

Deleting the bed carryover from the ash balance reveals ash recoveries of less than 85 mass percent. This implies that ash accumulated in the bed media. Observations of the bed media removed from the FBR after testing revealed that the silica media was discolored, apparently due

to ash material agglomerating to the silica media. Pictures of the before and after silica media are presented in Appendix D.

Comparing the mass of ash captured by the cyclone with the total ash captured allows determination of the collection efficiency of the cyclone. The collection efficiency of the cyclone was determined to average 97 percent during the testing.

5.1.6 Bed Media Characterization

Characterization of the starting silica bed material included size distribution, bulk density, and total metals analysis. The results of these analyses are presented in Tables 5-3 and 5-4 for comparison with subsequent samples taken after each pilot test run. The results show that 100 mass percent of the sample is sized within the range of 850 to 212 μm (20 by 65 mesh), and the mean particle size of the starting bed was between 490 and 520 μm . Traces of iron, aluminum, sulfates, and carbonates were found in the silica bed media. Lesser concentrations of other metals were also detected.

Samples of the bed media were taken at various times during the testing to determine if the characteristics of the bed were changing with time. Table 5-3 presents a summary of the particle size distribution measured for these samples. These results indicate a trend of increasing particle size from the start of the testing to the end. Visual inspection of the final bed revealed some particles as large as 2 cm (0.8 inches) in diameter.

Total metals analyses were conducted on these same bed media samples. Table 5-4 presents the results of these analyses. Concentrations of chromium, barium, lead, aluminium, calcium, iron, magnesium, potassium, sodium and zinc increased significantly as the testing progressed compared to the starting concentration of these metals in the bed media. Comparing the increase in bed metals concentration with the metals concentrations in the starting waste ("Bed/Waste Metal Ratio" in Table 5-4) provides an indication of the tendency of each metal to remain in the bed. This evaluation indicates that the bed media concentrations of phosphorus, potassium and sodium increased in greater proportions than other metals present in the waste feed. These three metals are known to agglomerate in silica based beds (see reference in Annex).

The increase in metals concentration in the bed media in conjunction with the increase in particle size, and visual observations of the bed media confirms that the bed media was agglomerating with waste ash during the testing. Since these increases occurred throughout the testing, it is concluded that agglomeration was occurring at all test conditions, not just at the higher temperatures. The bed agglomeration could have effected the fluidization characteristics and caused the bed temperatures measured at various points in the bed to diverge as was noted in Section 5.1.3.

Bed modifiers are often added to fluid bed systems when agglomeration is anticipated to occur. Bed modifiers alter the eutectic temperature for the silica and alkaline metal combinations. Kaolin clay is a frequently used modifier (see the reference material in Annex). These results indicate

that the full-scale process for incineration of the PMB waste must be equipped with the capability of adding a bed modifier, such as kaolin clay, to prevent or minimize agglomeration of the silica bed.

5.2 CONTINUOUS EMISSION MONITORING RESULTS

The offgas from the process (outlet of the baghouse) was monitored continuously for O₂, CO₂, CO, NO_x, SO₂, and THC. The last four are criteria pollutants that could impact the permitting of a full-scale process. The nine test cases were designed to evaluate the effect of bed temperature and offgas O₂ concentration on offgas concentrations of these four criteria pollutants. The results for each of these pollutants are summarized in Table 5-5.

5.2.1 Carbon Monoxide and Total Hydrocarbons

CO and THC are typically used as indicators of effective combustion in incineration systems. The regulatory limit for CO for incineration systems (40 CFR 264, Subpart O) is 100 ppm (dry volume, corrected to 7 volume percent oxygen) on a 60 minute rolling average basis (i.e., arithmetic average of the 60 most recent one minute averages). Under the boiler and industrial furnace (BIF) regulations (40 CFR 266), combustion systems processing hazardous waste as fuel or raw materials must meet the same 100 ppm CO limit or an alternative 20 ppm THC limit. The THC limit is evaluated on the same basis as CO (i.e., dry volume, corrected to 7 volume percent oxygen, 60 minute rolling average). Well designed and operated incineration systems can typically maintain CO and THC concentrations well below these values.

Combustion efficiency in incineration systems typically increases with increasing combustion temperature or increasing O₂ concentration in the combustion chamber. The results from the pilot testing were consistent with this statement. Figure 5-1 presents a graphical representation of the CO concentrations in the offgas from the FBR pilot process as a function of bed temperature and offgas O₂ concentration. All test cases at the lower O₂ concentration (i.e., approximately 5.5 volume percent) exhibited average offgas CO concentrations in excess of the 100 ppm regulatory limit. All the other test cases were in compliance with the 100 ppm CO limit. However, the data indicate that the process should be operated at bed temperatures in excess of 800°C (1,472°F) and offgas oxygen concentrations in excess of 7 volume percent to maintain a sufficient differential between the measured offgas CO and the regulatory limit.

The THC monitor was not functional during the second day of testing (test cases at a bed temperature of 877°C). The THC results from the other two days of testing exhibited the same trend as the offgas CO concentration. All test cases except for Case 1A (bed temperature of 779°C and offgas oxygen concentration of 5.7 volume percent) exhibited THC concentrations well below the 20 ppm BIF alternative regulatory limit.

5.2.2 Oxides of Nitrogen

Emissions of NO_x from combustion systems are generated from two sources; 1) nitrogen in the air (thermal NO_x) or 2) nitrogen in the fuel or waste (fuel NO_x). Thermal NO_x formation is primarily a function of the combustion chamber temperature. Generation of fuel NO_x is a function of the combustion chamber temperature, the nitrogen concentration in the fuel or waste, and the oxygen concentration in the offgas.

The Type II plastic has a significant organic nitrogen content (21 mass percent for B48 PMB waste from Table 3-3) compared to the Type V plastic (0.6 mass percent for B70 PMB waste) that can be a source of fuel NO_x . Therefore, contributions from both sources of NO_x described above will combine to determine the offgas NO_x concentration while burning any waste containing Type II plastic blasting media. When burning PMB waste that contains only Type V plastic, NO_x concentrations in the offgas would primarily be thermal NO_x .

Prior to initiating waste feed during each day of the testing, propane was fed to the bed to increase bed temperature. The offgas concentrations recorded during these periods provide an estimate of the concentrations that may be expected when burning wastes that contain little or no organic nitrogen. The data from these periods of operation is as follows:

Test Run	#1	#3
Bed Temperature ($^{\circ}\text{C}$)	747	761
NO_x (ppm)	152	324
SO_2 (ppm)	14	26
Offgas O_2 (vol %)	11.2	8.4

Comparing the daily startup and measured NO_x concentrations provides an indication of the relative impact of fuel NO_x compared to thermal NO_x for the waste mixture processed in the pilot test cases. Any PMB wastes processed that contained more organic nitrogen would likely exhibit higher concentrations of NO_x in the offgas at the same combustion temperature and offgas oxygen concentration assuming the nitrogen present in the waste is part of a similar structural group.

Since NO_x measurements include all oxides of nitrogen, it is expected that increased oxygen concentrations would increase the offgas NO_x concentration due to the higher availability of oxygen to combine with the organic nitrogen released during combustion. The results in Table 5-5 confirm this expectation. It was further expected that increased combustion temperature would increase the rate of conversion of nitrogen to the various oxides and therefore result in higher offgas NO_x concentrations. This expectation was also verified by the testing as shown in Table 5-5. Figure 5-2 presents a graphical representation of the NO_x results.

The nitrogen contained in the offgas NO_x represents an effective conversion of waste nitrogen ranging from 2.5 to 3.8 mass percent. The actual conversion of fuel nitrogen to NO_x ranged from approximately 1.2 to 3.0 mass percent if the apparent thermal NO_x component is omitted from the conversion calculation.

5.2.3 Sulfur Dioxide

One of the offgas components resulting from the sulfur in the waste is SO_2 . Unlike NO_x , concentrations of SO_2 decreased with increasing oxygen content in the offgas. This was likely caused by the increased oxidative state forcing the sulfur from the lower state of oxidation (SO_2) to a higher state (SO_3 or SO_4) thereby reducing the SO_2 concentration in the offgas. Increased bed temperature caused an increase in the offgas concentration of SO_2 . Results of SO_2 monitoring during the testing are presented in Table 5-5.

The SO_2 concentrations measured in the offgas represented sulfur conversions ranging from 27 to 114 mass percent of the measured sulfur content of the waste feed. In addition, significant sulfur recovery was measured in the sulfate concentration of the process residuals (see Section 5.4). These results indicate a small degree of inaccuracy in either the measurement of the sulfur content of the feed or the measurement of the SO_2 concentration in the offgas.

5.3 EMISSION SAMPLING RESULTS

Stack sampling trains were utilized to measure the offgas concentrations of the following:

- Volatile organics
- Semivolatile organics
- Dioxins and furans
- Particulates
- Metals
- Hydrogen chloride/chlorine (HCl/Cl_2)
- Hydrogen Cyanide (HCN).

Volatile organic emissions were measured using an EPA Method 0030 volatile organic sampling train (VOST). The semivolatile organics and dioxin and furans were measured using a EPA Method 0010 sampling train. The extract from the XAD resin tube from the Method 0010 sampling train was split for these separate analyses. Metal emissions were measured using a Multiple Metals sampling train. Emissions of HCl/Cl_2 and cyanide were measured with a Modified Method 0050 sampling train. Measurements of the particulate emissions were obtained from each sampling train except the VOST. Figures presenting the configuration of these sampling trains and train analytical results are included in the Annexes.

Table 5-6 presents a summary of all stack sampling results for each test run. All the results presented in Table 5-6 are listed as concentrations on a dry basis at standard conditions (20 °C and 1 atmosphere) and corrected to 7 volume percent oxygen. Spreadsheets showing the raw data used to calculate these stack concentrations are included in the Annexes.

5.3.1 Volatile Organics

Only five volatile organic compounds were consistently detected in the VOST samples; chloromethane, acrylonitrile, benzene, toluene, and styrene. These compounds were detected at relatively low concentrations. There were no significant differences in the measured emissions from one test run to the next.

5.3.2 Semivolatile Organics

The semivolatile organic compound found at the highest concentration in the offgas was bis(2-ethylhexyl)phthalate which is a common product of incomplete combustion (PIC) when burning plastic materials. There was a general decreasing trend in the measured emissions with increasing bed temperature for this compound.

5.3.3 Metals

Metal emissions from processes that use a baghouse for controlling metal emissions are typically a function of the particulate emissions and the concentration of the metals in the particulate. The metal determined to be in the highest concentration in the baghouse dust was cadmium. This observation is consistent with the highest metal mass emission rate measured from the pilot test process. The stack concentration of cadmium increased with increasing bed temperature. The increasing stack concentration for cadmium coincided with an increasing cadmium concentration in the baghouse dust. Offgas concentrations of metals with a low volatility (barium, chromium, iron, magnesium, and zinc) showed an opposite trend of decreasing offgas concentration with increasing bed temperature. This was due to the dilutional effect of the increasing cadmium concentration in the emitted particulate.

Table 5-7 presents a summary of system removal efficiencies (SRE) measured during the pilot testing. The average SRE for the three carcinogenic metals detected in the waste feed (arsenic, cadmium, and chromium) averaged greater than 99.95 percent.

5.3.4 Particulates

The pilot testing was conducted with new bags. The particulate loading on the bags was so low that the measurable baghouse pressure drop never increased during testing (i.e., a significant dust cake did not form). Therefore, offgas particulate concentrations measured during the pilot scale testing are likely to be conservative. The offgas concentrations of particulate averaged $18,208 \text{ Mg/m}^3$ ($0.0079 \text{ grains/ft}^3$), corrected to 7 volume percent oxygen. These concentrations are at standard conditions of 20°C and 1 atmosphere.

The bags used in the pilot test were new bags which allow more fine particulate to penetrate and pass through. After several hours of use, some of the larger interstitial channels in the cloth will fill and minimize particulate pass through. The dust loading to the baghouse during the pilot tests was low,

therefore preventing the formation of a dust cake. A dust cake enhances the particulate removal capability of a baghouse by adding additional resistance to particulate penetration. Therefore, the particulate and metals emissions measured during the pilot test runs were probably conservative compared to performance in a full scale system with seasoned bags.

5.3.5 Dioxins and Furans

Offgas concentrations of dioxins and furans ranged from 6.5 to 40.2 ng/m³ (dry basis, 1 atm, 20°C, corrected to 7 volume percent oxygen) expressed as total dioxins and furans and 0.14 to 0.64 ng/m³ (dry basis, 1 atm, 20 °C, corrected to 7 volume percent oxygen) expressed as tetrachlorodibenzo(para)dioxin (TCDD) equivalent.

Studies conducted by the EPA have shown that increased residence time of combustion offgases at a temperature between 232 and 454°C (450 and 850°F) correspond to increased emissions of dioxin and furans (USEPA, "Municipal Waste Combustion Study: Combustion Control of Organic Emissions", EPA/530-SW-87-021C, NTIS Order No. PB87-206090). The Hazen pilot process was equipped with an uninsulated cyclone separator and water cooled heat exchanger that slowly cooled the offgas through the temperature range optimum for dioxin and furan formation. A full scale process could be designed with an insulated cyclone to maintain the offgas temperature above 454°C (850°F) prior to entering a partial quench. The partial quench would rapidly cool the combustion gases to a temperature less than 232°C (450°F) thereby minimizing the residence time the combustion gases are maintained at the optimum temperature for dioxin and furan formation. Therefore, it is expected that the offgas concentration of dioxin and furans from a full scale process would be lower than those measured in this pilot test.

5.3.6 Hydrogen Chloride/Chlorine

Emissions of chlorides as HCl/Cl₂ averaged approximately 55,000 Mg/dscm which was equivalent to 0.004 kg/h (0.01 lb/h). Approximately 20 mass percent of the total chlorine/chloride in the waste feed was captured in the cyclone and baghouse dust likely as metal chlorides. The predicted emissions of HCl/Cl₂, assuming the remaining chlorine/chloride in the waste feed is emitted as HCl/Cl₂, would be 0.003 kg/h (0.007 lb/h) which is similar to the measured value.

5.3.7 Hydrogen Cyanide

The organic nitrogen content of the plastic media provides the potential for generation of hydrogen cyanide (HCN). Combustion of plastics containing organic nitrogen may produce measurable quantities of HCN, particularly at temperatures less than 760°C (1,400°F). The pilot test results indicate HCN was generated in all three test runs and that the emissions decreased significantly with increasing bed temperature.

5.3.8 Comparison With Regulatory Limits

To minimize emissions, a full-scale process would likely be operated at conditions more similar to those demonstrated in Pilot Test Run #2. Table 5-8 presents a summary of the projected emissions from a full-scale process operating at a nominal capacity of 227 kg/h (500 lb/h). The projected emissions were calculated by scaling up the emissions from Pilot Test Run #2. The projected emissions are compared to current and potential regulatory limits in Table 5-8.

Regulatory limits listed as having the Boiler and Industrial Furnace (BIF) regulations or the State of Utah Air Toxics Policy (Utah) as their source were obtained by dividing the applicable ambient air standard from the regulations by a site specific dispersion factor. The site specific dispersion factor was calculated as a maximum annual average using the Industrial Source Complex Short Term (ISCST2). Assumptions used in the modeling included:

- Noncomplex, rural terrain
- Stack height of 9.14 m
- Stack diameter of 0.38 m
- Stack exit temperature of 182°C
- Stack exit velocity of 18 m/s
- No building downwash.

Projected emissions of metals and volatile and semivolatile organics are orders of magnitude less than the potential standards.

Particulate emissions are an order of magnitude less than the current regulatory limit for incinerators of 185,300 Mg/m³ (0.08 grains/dscf, corrected to 7 volume percent oxygen) imposed under 40 CFR 264, Subpart O. The EPA is currently considering lowering the particulate emission limit to a much more stringent value of 11,581 Mg/m³ (0.005 grains/dscf, corrected to 7 volume percent oxygen). The pilot test data indicates that a process equipped with a baghouse alone for particulate control may require a wet electrostatic precipitator (WESP) to meet the potential limit, if imposed. As was discussed in Article 5.3.4, the actual particulate emissions would likely be less than those measured during the pilot test after the bags in the baghouse have been conditioned. Therefore, a process equipped with a baghouse may meet the regulatory standard for particulate without additional equipment, even if the more stringent limit were imposed.

The only EPA regulatory standard associated with emissions of dioxins and furans is the 6-nines Destruction and Removal Efficiency (DRE) imposed on facilities that process dioxin containing waste (40 CFR 264, Subpart O). This limit is only applicable when processing dioxin containing wastes (RCRA listed hazardous wastes labeled with an F020, F021, F022, F023, F026, or F027 waste code) and the PMB waste is not a dioxin containing waste. However, the EPA is currently considering imposing stack gas concentration limits on emissions of these compounds. Limits being considered are 5.4 to 9.7 ng/m³ (dry basis, 1 atm, 20°C, corrected to 7 volume percent oxygen) for total dioxin and furans and 0.12 to 0.17 ng/m³ (dry basis, 1 atm, 20°C, corrected to 7 volume percent oxygen) expressed as TCDD equivalents. Total (Dioxin and Furan) and TCDD equivalent data from the two test runs at higher bed temperatures were essentially identical to these anticipated limits. As was

discussed in Article 5.3.5, the full-scale process is likely to have lower emissions of dioxins and furans with minor design modifications.

The estimated HCl/Cl_2 emission rate from a 227 kg/h full scale unit based on the pilot test data is 0.1 kg/h (0.23 lb/h). The current regulatory limit for emissions of HCl is less than 1.82 kg/h (4.0 lb/h) or greater than 99 percent removal (40 CFR 264, Subpart O). Therefore, the pilot test data indicates the full scale process would comply with the current regulatory limit for emissions of HCl.

Projected emissions of HCN from a full scale unit processing waste at 227 kg/h are well below the allowable levels calculated using the Reference Air Concentration from the BIF regulations.

5.4 RESIDUALS CHARACTERIZATION

The two primary residuals resulting from combustion of the PMB waste in the FBR are ash collected in the cyclone and baghouse. Table 5-2 presented ash recoveries from the pilot scale testing. The majority of the ash (greater than 97 mass percent) was collected in the cyclone. Samples of both the cyclone and baghouse ash were collected from each test run and analyzed for particle size distribution, bulk density, and metals content.

A summary of the particle size analyses using a dry screen analysis is presented in Table 5-9. These results indicate the mean particle size of the ash captured in the cyclone (65 to 100 μm) is less than the mean particle size of the ash captured in the baghouse (135 to 170 μm).

The mean particle size of the baghouse catch was expected to be smaller than that of the cyclone catch. Therefore, the particle size distribution data in Table 5-9 is suspect. The particle size distribution of samples of the minus 150 μm fractions of the cyclone and baghouse catch were measured using an alternative technique known as a Bahco analysis. The Bahco analysis is performed with a microparticle classifier that segregates particles in terminal velocity ranges. These terminal velocity ranges are then converted to equivalent particle sizes using Stokes law.

Table 5-10 presents a summary of the particle size analysis for a representative sample of the cyclone and baghouse catch using the Bahco analysis. These results indicate a much smaller mean particle size for the baghouse sample than those reported in Table 5-9 from the dry screen analysis. The larger particle size for the baghouse catch using the dry screen analysis could be attributed to particle clumping and screen blinding. Results from the Bahco analysis are included in the Annexes.

The smaller particle size for the baghouse ash resulted in a lower bulk density for the baghouse ash (0.4 g/cm^3 , packed) compared to the cyclone ash (1.47 g/cm^3 , packed excluding Test #3). The particle size analyses in Table 5-9 for the cyclone catch also reflects the bed carryover that was visible in the cyclone ash from Test #3.

A summary of the metals analyses for the cyclone and baghouse ash samples is presented in Table 5-11. The metals concentrations in the starting waste and muffle roasted ash from pre-pilot test activities have been included in Table 5-11 for reference.

Metals that are typically considered to be volatile metals include mercury, cadmium, lead, potassium, and sodium. The results consistently demonstrate that the concentration of these metals are higher in the baghouse ash than the cyclone ash. This is caused by condensation of the volatilized metals onto the smaller particles that are captured in the baghouse. The increased concentration of volatile metals in the baghouse dust causes a dilutional effect on metals considered to be nonvolatile, such as aluminum, barium, calcium, chromium, iron and magnesium. Therefore, concentrations of these nonvolatile metals tend to be lower in the baghouse dust than in the cyclone ash. This was not true for Test Run #3 where the concentrations of metals in the cyclone ash were diluted by the bed carryover.

Table 5-12 presents the ratio of ash concentrations for the baghouse and cyclone ash for all three tests. The data in Table 5-12 has been organized in decreasing order of the average ratios. Metal chlorides are typically much more volatile than metal oxides or the pure metal which would account for the highest ratio being determined for the chloride anion. The ratios calculated for Test Run #3 are much higher than the ratios for the other two test runs reflecting the effect of the bed carryover.

The silicon content of the cyclone ash compared to the ash from the muffle roasted waste again confirms that bed carryover was occurring in all three test runs. The increased silicon concentration of the cyclone ash from Test Run #3 is an additional confirmation of the increased bed carryover observed in that test run.

The sulfate concentrations measured in the residuals indicate a tendency to accumulate in the smaller particles (baghouse dust). The mass of sulfur recovered in the residuals represented an average of 12 mass percent of the sulfur in the starting waste. The recovery of sulfur in the residuals decreased with increasing bed temperature (i.e., Test Run #1 - 16 mass percent, Test Run #2 - 12 mass percent, Test Run #3 - 9 mass percent).

6.0 STABILIZATION TEST RESULTS

6.1 INTRODUCTION

The starting waste was RCRA characteristically hazardous due to leachability of metals. These same metals are present in the ash from the fluid bed combustion process at much higher concentrations due to volume reduction of the PMB waste. Therefore, the ash resulting from the combustion process remains a characteristically hazardous waste, but in a significantly smaller volume of material (approximately 95 percent less volume). The resulting ash must be managed in some manner.

One alternative is land disposal. However, prior to land disposal the ash must be treated to remove the characteristic hazard. Stabilization is the technology required by 40 CFR 268 (Land Ban) for treatment of materials that are hazardous due to the leachability of metals. Therefore, one of the objectives of the pilot test was to prepare a representative sample of the ash from the combustion process and conduct stabilization tests to determine if the characteristic hazard of metal leachability can be removed.

Stabilization requires addition of materials such that the mass of material finally requiring disposal could be significantly greater than the starting quantity of ash. The cost of these additives and cost for disposal of the resulting mass of stabilized materials may necessitate a more detailed stabilization test that would more precisely identify the optimum mix that minimizes the cost of additives and final mass of materials requiring disposal. The purpose of the stabilization tests in this work was to determine if the ash could be stabilized.

6.2 ASH COMPOSITE SAMPLE

There were two primary residuals resulting from the fluid bed combustion process; cyclone ash and baghouse dust. Characterizations of these two residuals were presented in Section 5.0 of this report. The cyclone ash represented approximately 96 weight percent of the total mass of material from these two residual streams. An ash composite sample was generated for stabilization testing from the cyclone ash and baghouse dust collected during the three pilot test runs. Table 6-1 presents a summary of the weight percent of each residual stream from the pilot test used to form the ash composite sample for stabilization testing.

6.3 STABILIZATION TEST RESULTS

An aliquot of the ash composite sample was analyzed using the Toxicity Characteristic Leaching Procedure (TCLP) test to identify the baseline leachability of the metals contained in the sample.

Results from the TCLP test of the ash composite sample are presented in Table 6-2. The results indicate that the ash composite sample fails to comply with the TCLP limit for cadmium and chromium. Although barium and lead were present in the ash composite at significant concentrations, analysis of the leachate from the TCLP test indicated these two metals were in a stabilized form.

Aliquots of the ash composite sample were mixed with various media typically used to stabilize metals. The three media used were fly ash, Type II Portland cement and blast furnace slag. Samples of the fly ash and blast furnace slag used as stabilizing agents were analyzed for major and trace metals using an x-ray fluorescence spectrophotometric scan. The results of this scan are summarized in Table 6-3 for reference.

A total of six mixtures were made and blended with water to form a slurry. Each slurry was poured into a mold and allowed to cure for approximately 8 days. After curing, each compact was analyzed using the TCLP test. Table 6-2 presents the composition of each compact and the resulting TCLP analysis.

The results indicate that Type II Portland cement alone reduces chromium leachability, has little effect on the leachability of cadmium, and significantly increases the leachability of lead (Compact #1). Addition of fly ash to the mixture stabilizes cadmium and lead but increases the leachability of chromium (Compact #2). Addition of sodium sulfide (Na_2S) with smaller quantities of Type II Portland cement and fly ash produced a compact that passed all of the TCLP leaching criteria (Compact #3). The final three compacts contained Type II Portland cement and ground blast furnace slag at varying mixtures. All three of these compacts passed the TCLP leaching criteria. The lowest bulking factor for a compact passing the TCLP leaching criteria was approximately 1.8 grams of mixture per gram of ash.

7.0 DESIGN AND OPERATIONAL CONSIDERATIONS

7.1 WASTE PROFILE

The PMB waste generated at Hill Air Force Base (HAFB) and other facilities are currently being disposed of at USPCI by stabilization and landfilling at a cost of \$1.08/kg (\$980/ton). A cost/benefit evaluation of the proposed fluid bed combustion process compared to current waste management practices would be impacted heavily by the profile (quantity and characterization) of the PMB waste planned for processing. The pilot testing demonstrated that a fluid bed combustion process is an efficient technology for accomplishing significant volume reduction on PMB wastes. However, waste streams such as the B50 stream from HAFB would leave significant residue after combustion that require additional management.

Using the 1993 HAFB PMB waste profile from Table 3-1 as an example, 129 metric tons of PMB waste would have resulted in approximately 21 metric tons of ash residue (before stabilization) requiring management (17 metric tons from the B50 waste stream and 4 metric tons from all other waste streams).

Therefore, a better definition of the waste profile (characterization and quantity) and summary of current waste management practices and costs is essential for conducting an effective cost/benefit evaluation.

7.2 OPERATING FACTOR

The actual capacity of the full scale fluid bed process compared to the design capacity is directly related to the operating factor. A one shift a day, five days per week operating schedule was requested for the full scale process. This translates into an operating factor of 0.24 (assuming maintenance can be conducted on the off shifts). The same process operating 24 hours per day, 7 days per week would have an operating factor of approximately 0.85 (assuming 0.15 for maintenance and miscellaneous downtime) and could process 3.5 times more waste than the same process operated only one shift per day, five days per week. The resulting cost per unit mass for processing the waste decrease by distributing the fixed annual capital cost recovery over a larger volume of waste being processed. This would result in a decrease of the unit treatment cost by a factor of approximately 2. Therefore, the requirement for one shift per day operation has a significant impact on the unit treatment cost and should be reconsidered.

7.3 METAL RECYCLE

Since the ash residues contain significant concentrations of cadmium and lead, recycle for metal recovery was considered as an alternative for management of the ash residues. Three companies in the business of recycling metals are Horsehead Resource Development Company (HRDC), Inmetco, and Encycle. Recycling facilities operated by these three companies have minimum limits for concentrations of specific metals in the wastes that they can receive for metal recycle.

Of these three companies, Encycle was the only company with minimum feed metal concentration limitations low enough to accept the ash from the fluid bed combustion process as a material for recycle. The cost for managing the ash through the recycling process was quoted at \$200 per drum or \$500 per metric ton if delivered in bulk. The contact for Encycle was Jeff Cohen at (404) 350 - 0216.

8.0 CONCLUSIONS

Specific conclusions that can be stated as a result of the pilot test activities include:

The annual mass of PMB waste generated at Hill Air Force Base (HAFB) is approximately 123 metric tons (142 tons).

The Type II plastic blasting media has a significant organic nitrogen content (approximately 21 mass percent).

The B48 and B70 PMB waste streams have ash contents of approximately 2.5 and 6.7 mass percent, respectively.

The B50 waste stream contains inert material (garnet and ash) at a concentration of approximately 65 mass percent.

A bed fluidizing air velocity of approximately 0.75 m/s (2.5 ft/s) was determined to be optimum using silica as a bed media. A fluidizing velocity of 0.85 m/s was used successfully in the pilot tests with silica as the bed media.

The combined residence time for the combustion gas in the fluid bed and freeboard should be a minimum of 3.5 seconds.

Total ash recovery was approximately 81 mass percent. The remainder of the ash was retained in the bed by agglomerating to the bed media. Use of a bed modifier (Kaolin clay) will be required to minimize agglomeration of the ash to the bed media.

The cyclone particulate removal efficiency was approximately 97 weight percent.

At a bed fluidizing velocity of 0.85 m/s, approximately 20 mass percent of the ash captured in the cyclone and baghouse was a result of bed media carryover.

The average particle size of the bed media increased during the pilot test runs due to agglomeration of the bed media with ash residues from the waste.

Concentrations of phosphorus, sodium and potassium in the bed media increased much more rapidly than other metals compared to the feed rates of these metals to the system. This also indicates agglomeration of the bed media.

Offgas concentrations of carbon monoxide and total hydrocarbons decreased with increasing bed temperature at constant offgas oxygen concentrations. Offgas concentrations of carbon monoxide and total hydrocarbons decreased with increasing offgas oxygen concentrations at constant bed temperatures.

Offgas concentrations of NO_x increased with increasing bed temperature at constant offgas oxygen concentrations. Offgas concentrations of NO_x increased with increasing offgas oxygen concentrations at constant bed temperatures. Concentrations of NO_x in the offgas ranged from 416 to 858 ppm by volume.

Conversion of organic nitrogen to NO_x averaged approximately 3.3 mass percent.

Offgas concentrations of SO_2 typically increased with increasing bed temperature at a constant offgas oxygen concentration. Offgas concentrations of SO_2 typically decreased with increasing offgas oxygen concentrations at a constant bed temperature. Offgas concentrations of SO_2 ranged from 21 to 90 ppm by volume.

Detectable emissions of hydrogen cyanide were measured during all three pilot test runs. The offgas concentration of hydrogen cyanide decreased with increasing bed temperature.

Fluid bed combustion processes burning PMB waste should be operated at bed temperatures between 800 and 900°C and offgas oxygen concentrations greater than 9 percent by volume to minimize emissions.

The concentration of cadmium in the baghouse dust increased with increasing bed temperature. As a result, the corresponding emissions of cadmium in the offgas from the baghouse also increased.

The lowest stack concentration of total tetra through octa dioxins and furans was 6.5 ng/m³ measured at a bed temperature of 877°C and an offgas oxygen concentration of 7 volume percent. The corresponding tetrachlorodibenzo(a)para)dioxin (TCDD) toxic equivalent emission rate was 0.12 ng/m³. These measurements are on a dry basis at 1 atmosphere and 20°C, corrected to 7 volume percent oxygen. These values are essentially equal to proposed regulatory limits that may be applied to a future full-scale system (EPA Combustion Emission Technology Resource Document, CETRED). Modifications to the full-scale process design compared to the pilot scale process should decrease the offgas concentrations of dioxins and furans below those measured in the pilot test.

Concentrations of particulate in the offgas averaged 18,200 Mg/m³ (0.0079 grains per dry standard cubic foot) corrected to 7 volume percent oxygen. This value is an order of magnitude less than the current regulatory limit and essentially equal to the proposed regulatory limit that may be applied to the future full-scale process (CETRED). Conditioning of the bags and development of a dust cake on the bags should decrease the particulate emissions from a full-scale process compared to the pilot test.

System removal efficiencies for metals were greater than 99.9 mass percent for those metals which were present at concentrations greater than 100 mg/kg in the starting waste. This indicates

that a full-scale process equipped with a baghouse will be able to meet the metal emission standards.

Concentrations of cadmium and lead were significantly higher in the baghouse dust than in the cyclone ash during the pilot test. This data indicates these two metals have higher volatility than other metals.

The ash residue can be stabilized to meet the regulatory standards for leachability using mixtures of ash, Type II Portland cement and blast furnace slag.

Table 3-1. PMB Waste Survey Summary (1/1/93 to 1/1/94)

Waste Type	Waste Name	Site Information		Phone No.	Generation Rate ^a		Metals in the Waste (TCLP, mg/l) ^b					
		Number	Contact		(kg)	% of Total	Al	Ba	Cd	Cr	Pb	
II	B48 (Bags)	N03B	Roger Murray	(801) 777-1026	486	0.4	X		X			
		N04A	Roger Murray	(801) 777-1026	27,211	21.0	X		X			
		N10D	Breck Baker	(801) 777-4421	5,514	4.3		2.0	15	6	1.2	
		N21B	Breck Baker	(801) 777-4421	17,831	13.6		5.0	31	134	0.5	
		N11E	Mark Peery	(801) 777-3569	0	0.0						
		T120	Sharon Stephenson	(801) 777-6618	1,667	1.3						
		TB11	Dan Nielson	(801) 777-0670	0	0.0						
		N03B	Roger Murray	(801) 777-1026	3,532	2.7		1.5	33	5	0.2	
		N04A	Roger Murray	(801) 777-1026	1,189	0.9		3.0	41	6	0.2	
		N04B	Dave Chesley	(801) 777-2053	9,821	7.6		3.0	371	9	3.4	
		N10A	Jay Stoddard	(801) 777-4830	745	0.6		1.4	47	22	0.5	
V	B50 (drums)	N10D	Breck Baker	(801) 777-4421								
		L114	George Mullen	(801) 777-2782								
		L116	Anthony Walton	(801) 777-2795								
		L121	Michael McCoy	(801) 777-4969								
		L122	Michael Phillips	(801) 777-0702								
		L123	James Ipson	(801) 777-2795								
		K06H	Jay Ramond	(801) 777-3910	24,492	18.9		1.7	11	9	0.9	
		TT04	Ed Snyder	(801) 777-3033	1,196	0.9		3.5	31	147		
		LA28	J. D. Chrispensen	(801) 777-9077	7,658	5.9			X	X		
		LA29	J. D. Chrispensen	(801) 777-9077	0	0.0			X	X		
		LA30	J. D. Chrispensen	(801) 777-9627	27,980	21.6			X	X		

New Waste Streams in 1994

Notes:
a) Generation rates for calendar year 1993 were obtained from personnel at HAFB. The contact at HAFB was Cheryl Ferguson (801-777-6781).
b) 'X' denotes waste is likely to contain these metals but TCLP analytical data was not provided

Table 3-2. Waste Particle Size Distribution Data

Sieve Size		Cumulative Mass Percent Passing					
		B70 Waste		B48 Waste		B70/B48 Composite	B50 Waste
mesh	μm	Classifier	Baghouse	N04A	N03B		
20	850	99.8	99.5	99.9	100.0	99.9	99.1
28	600	99.7	96.1	99.8	100.0	98.6	96.9
35	425	99.5	84.0	97.6	100.0	94.0	90.4
48	300	46.4	63.6	82.6	99.4	73.0	84.0
65	212	19.4	56.3	66.4	98.6	55.0	77.8
100	150	5.6	46.0	53.7	96.4	39.6	69.3
150	106	0.8	26.3	42.6	89.1	27.4	54.4
200	75	0.1	8.1	29.3	77.4	17.5	35.0
270	53	0.0	2.4	25.3	61.0	11.9	18.6
325	45	0.0	1.6	12.3	44.6	7.1	13.4
400	38	0.0	0.8	6.9	31.1	4.3	9.9
Pan		0	0	0	0	0	0
Mean Particle Size (μm)		320 - 340	170 - 180	130 - 140	47 - 49	190 - 200	90 - 100
Bulk Density (g/cm^3)							
Loose		0.62	0.58	0.69	0.68	0.68	1.11
Packed		0.73	0.80	0.96	0.94	0.87	1.50

Table 3-3. PMB Waste Elemental Analysis

Analyte	Pilot Test Samples			B50 ^b Waste
	B70 Waste (Type V)	B48 Waste (Type II)	B70/B48 ^a Composite	
Moisture	0.67	6.25	3.15	0.87
Carbon	56.41	38.06	47.54	20.99
Hydrogen	7.44	6.01	6.48	2.88
Nitrogen	0.6	21.0	10.7	1.86
Sulfur	0.11	0.08	0.09	0.09
Chloride	0.03	0.13	0.08	0.04
Ash	6.67	2.54	4.01	65.44
Oxygen	28.07	25.93	27.95	7.87
Heating Value (kJ/kg)	25,005	15,747	20,915	8,702
Heating Value (Btu/lb)	10,750	6,770	8,992	3,741

Notes:

- a) The composite consisted of 53.4 % B48 Waste and 46.6 % B70 Waste by mass.
- b) The B50 waste consists primarily of Garnet blended with plastic media.
- c) All results are on a wet basis.

Table 3-4. Metal Content of Waste Samples

Metal Analyte	Metals Concentration (mg/kg)			
	B70/B48 Composite		B50 Waste	
	Waste	Waste Ash ^a	Waste	Waste Ash ^a
RCRA Metals				
Arsenic	2	9	8	7
Beryllium	< 50	< 50	< 50	< 50
Cadmium	985	5,000	85	50
Chromium	1,100	24,450	440	550
Antimony	80	325	< 50	< 50
Barium	1,250	28,700	245	320
Lead	320	4,780	725	940
Mercury	< 0.1	< 0.1	< 0.1	< 0.1
Silver	8	123	< 2	< 2
Thallium	< 50	< 50	< 50	< 50
Other Parameters				
Aluminum	3,750	29,500	74,050	106,500
Calcium	1,000	26,750	5,200	8,660
Carbon	475,400	NA	209,900	NA
Chloride	800	NA	400	NA
Copper	65	1,175	80	120
Iron	1,680	30,800	165,000	239,500
Magnesium	245	17,900	8,535	12,800
Nickel	< 10	130	40	60
Phosphorus	< 10	762	515	803
Potassium	40	4,445	445	635
Selenium	< 0.5	< 0.5	< 0.5	< 0.5
Silicon	7,350	128,000	83,700	127,500
Sodium	150	1,275	255	430
Sulfate	NA	25,000	NA	1,900
Zinc	790	18,050	590	765

Notes:

- a) Waste plastic ash was generated by muffle roasting an aliquot of the waste at 900 °C.
b) NA = Not Analyzed

Table 3-5. Summary of Dust Explosion Test Results

Parameter	Test Result	Units
DUST EXPLOSION RISK		
Maximum Explosion Pressure	7.7	bar
Maximum Rate of Pressure Rise	434	bar/s
Kst Value	118	bar-m/s
Minimum Ignition Energy	100 - 300	mJ
Minimum Ignition Temperature (Dust Cloud)	440 - 460	°C
Minimum Oxygen Concentration	12 - 15	vol %
Minimum Explosible Concentration	45 - 50	g/m ³
ELECTROSTATIC RISK		
Powder Resistivity (44 % relative humidity)	4.2E+11	ohm-m
Powder Resistivity (8 % relative humidity)	1.1E+12	ohm-m
Charge Decay Time (44 % relative humidity)	54	s
Charge Decay Time (7 % relative humidity)	189	s

Table 4-1. Process Monitoring and Sampling

Monitored Parameter	Parameter ^a Label	Measurement Device	Measurement Frequency	Recording Frequency	Calibration Frequency
FEED/FLOW RATES					
Waste Plastic Media	F1	Weigh Scale ^b	Continuous	30 min	Prior to Testing
Waste Feed Transfer Air	F2	Orifice Plate	Continuous	30 min	Prior to Testing
FBR Cooling Water	F3	Rotameter	Continuous	30 min	Prior to Testing
Fluidizing Air	F4	Orifice Plate	Continuous	30 min	Prior to Testing
Cyclone Ash	F5	Weigh Scale ^b	Manual	Hourly	Prior to Testing
Heat Exchanger Cooling Water	F6	Rotameter	Continuous	30 min	Prior to Testing
Baghouse Ash	F7	Weigh Scale ^b	Manual	Hourly	Prior to Testing
Baghouse Outlet	F8	Orifice Plate	Continuous	30 min	Prior to Testing
TEMPERATURES^{c, d}					
Windbox	T1A	Thermocouple	Continuous	Continuous	Prior to Testing
Windbox	T1B	Thermocouple	Continuous	Continuous	Prior to Testing
Bed - 6" (0 degrees)	T2A	Thermocouple	Continuous	Continuous	Prior to Testing
Bed - 6" (120 degrees)	T2B	Thermocouple	Continuous	Continuous	Prior to Testing
Bed - 6" (240 degrees)	T2C	Thermocouple	Continuous	Continuous	Prior to Testing
Bed - 12" (0 degrees)	T3	Thermocouple	Continuous	Continuous	Prior to Testing
Bed - 18" (0 degrees)	T4A	Thermocouple	Continuous	Continuous	Prior to Testing
Bed - 18" (120 degrees)	T4B	Thermocouple	Continuous	Continuous	Prior to Testing
Bed - 18" (240 degrees)	T4C	Thermocouple	Continuous	Continuous	Prior to Testing
Bed - 24" (0 degrees)	T5	Thermocouple	Continuous	Continuous	Prior to Testing
Bed - 30" (0 degrees)	T6	Thermocouple	Continuous	Continuous	Prior to Testing

Table 4-1. Process Monitoring and Sampling

Monitored Parameter	Parameter Label	Measurement Device	Measurement Frequency	Recording Frequency	Calibration Frequency
TEMPERATURES c, d (continued)					
Bed - 36" (0 degrees)	T7	Thermocouple	Continuous	Continuous	Prior to Testing
Freeboard - 72"	T8	Thermocouple	Continuous	Continuous	Prior to Testing
Freeboard - 93"	T9	Thermocouple	Continuous	Continuous	Prior to Testing
FBR Outlet	T10	Thermocouple	Continuous	Continuous	Prior to Testing
Cyclone Separator Outlet Gas	T11	Thermocouple	Continuous	Continuous	Prior to Testing
Heat Exchanger Outlet Gas	T12	Thermocouple	Continuous	Continuous	Prior to Testing
Baghouse	T13	Thermocouple	Continuous	Continuous	Prior to Testing
Baghouse Outlet Gas	T14	Thermocouple	Continuous	Continuous	Prior to Testing
Ambient	TA	Thermocouple	Continuous	Start/Finish	None
PRESSURES					
Bed Differential	DP1	Diff. Pressure Cell	Continuous	Continuous	Prior to Testing
Cyclone Differential	DP2	Magnahelic Gauge	Continuous	30 min	Prior to Testing
Baghouse Differential	DP3	Magnahelic Gauge	Continuous	30 min	Prior to Testing
Baghouse Outlet	P1	Magnahelic Gauge	Continuous	30 min	None
Ambient Barometric	PA	Barometer	Continuous	Start/Finish	None
Oxygen	A1	NDIR	Continuous	Continuous	Daily
Carbon Monoxide	A2	NDIR	Continuous	Continuous	Daily
Carbon Dioxide	A3	NDIR	Continuous	Continuous	Daily
Sulfur Dioxide	A4	Pulsed Fluorescent	Continuous	Continuous	Daily
Nitrogen Oxide	A5	Chemiluminescence	Continuous	Continuous	Daily
Total Hydrocarbons	A6	FID	Continuous	Continuous	Daily

MONITOR W01
22507
22508

Table 4-1. Process Monitoring and Sampling

Monitored Parameter	Parameter ^a Label	Measurement Device	Measurement Frequency	Recording Frequency	Calibration Frequency
SAMPLING POINTS					
FBR Bed	S1	NA	End of Test	End of Test	NA
Cyclone Ash	S2	NA	Hourly	Hourly	NA
Baghouse Ash	S3	NA	Hourly	Hourly	NA
Metals/Particulate Emissions	S4	MMT Sampling Train	Each Test	NA	NA
Volatile Emissions	S5	VOST	Each Test	NA	NA
Semivolatile Emissions	S6	M0010 Sampling Train	Each Test	NA	NA
Dioxin and Furan Emissions	S6	M0010 Sampling Train	Each Test	NA	NA
HC/Cl ₂ Emissions	S7	MM5 Sampling Train	Each Test	NA	NA
Hydrogen Cyanide Emissions	S7	MM5 Sampling Train	Each Test	NA	NA

NA - Not Applicable

^a Refer to Figure 4-2 for general monitoring instrument locations.

^b The duration associated with the change in mass is used to calculate the rate.

^c Thermocouple locations are based on heights above the fluid reactor base.

^d Thermocouples at the 6" and 18" heights above the fluidizing plate are located at 120° angles around the bed. The 0° thermocouple is located nearest the waste feed port.

Table 5-1. Summary of Fluid Bed Reactor Pilot Test Operating Data

Test Parameter	Units	Test Run #1			Test Run #2			Test Run #3		
		Case 1A	Case 1B	Case 1C	Case 2A	Case 2B	Case 2C	Case 3A	Case 3B	Case 3C
FLUID BED REACTOR										
Thermal Duty	GJ/h	0.25	0.21	0.18	0.22	0.20	0.18	0.25	0.21	0.17
Waste Feed Rate	kg/h	12.0	10.1	8.7	10.3	9.4	8.4	11.8	10.1	7.9
Cooling Water Flow Rate	ml/min	230	215	140	190	125	115	0	90	0
Fluidizing Air Flow Rate	m ³ /min (s)	1.23	1.22	1.25	1.12	1.12	1.12	1.21	1.19	1.14
Bed Inlet Gas Velocity ^a	m/s	0.88	0.85	0.88	0.85	0.85	0.85	1.01	1.01	0.94
Bed Temperature	°C	779	780	775	879	877	876	965	967	965
Bed Inlet Pressure	kPa	110	110	110	110	110	110	110	110	110
Bed Residence Time	s	1.8	1.8	1.7	1.8	1.8	1.8	1.5	1.5	1.6
Freeboard Temperature	°C	708	730	760	795	842	817	850	865	871
Freeboard Residence Time	s	1.7	1.8	1.9	1.9	2.0	2.0	2.0	1.8	2.1
Bed Pressure Drop	kPa	7.3	7.5	7.2	7.1	7.1	7.1	7.2	7.3	7.2
AIR POLLUTION CONTROL SYSTEM										
Baghouse Inlet Gas Temperature	°C	194	179	188	171	183	178	188	180	183
Baghouse Pressure Drop	kPa	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
Baghouse Air-to-Cloth Ratio ^b	m/min	0.59	0.52	0.50	0.49	0.45	0.48	0.46	0.49	0.42

cell = Standard Conditions of 20°C and 1 atmosphere pressure

(s) - Standard Conditions of 20°C and 1 atmosphere pressure

Notes:

a) Based on the fluidizing air flow rate at the bed temperature and pressure.

b) Air-to-Cloth ratio is based on the baghouse having 16 bags, each being 10.2 cm (4 inches) in diameter and 1.22 meters (4 feet) long.

Table 5-2. Summary of Pilot Test Ash Recovery

Test Parameter	Units	Test Run # 1 (9/14/94)	Test Run # 2 (9/15/94)	Test Run # 3 (9/16/94)
Process Conditions				
Bed Inlet Gas Velocity ^a	m/s	0.87	0.85	0.98
Bed Temperature	°C	778	877	966
Bed Pressure	kPa	110	110	110
Ash Recovery				
Total Waste Feed	kg	93	103	108
Total Ash Feed	kg	3.729	4.130	4.337
Total Cyclone Ash	kg	3.803	4.070	5.701
Daily Baghouse Ash	kg	0.157	0.124	0.114
Cyclone Efficiency ^b	mass %	96	97	98
Ash Recovery ^c	mass %	106	102	134
Bed Carryover ^d	kg	1.04	0.77	2.62
Ash Recovery ^e	mass %	78	83	74
Baghouse Cleanout ^f	kg	0.4		
Total Ash Recovery ^g	mass %	81		

Notes:

- a) Based on the fluidizing air flow rate at the bed temperature and pressure.
- b) Ash recovered in the cyclone as a percent of the total mass of ash recovered.
- c) Calculated for each test run with no accounting for bed carryover.
- d) Bed carryover was calculated by conducting a silicon balance on the ash stream.
- e) Calculated for each test run taking into account bed carryover.
- f) Dust collected during decommissioning of the baghouse.
- g) Calculated for the entire program considering baghouse dust collected during cleanout and calculated bed carryover.
- h) Unrecovered ash could likely be found in agglomerated bed particles.

Table 5-3. Fluid Bed Media Particle Size Distribution Data

Sieve Size		Cumulative Weight Percent Passing				
		Starting Bed	Daily Ending Bed Samples			Final Bed
mesh	μm		9/14/94	9/15/94	9/16/94	
20	850	99.9	99.9	99.8	99.5	99.3
28	600	90.6	84.9	82.5	75.6	72.1
35	425	12.3	17.5	16.0	11.8	7.2
48	300	0.8	0.5	0.4	0.2	0.6
65	212	0.0	0.1	0.1	0.1	0.2
100	150	0.0	0.0	0.0	0.0	0.1
150	106	0.0	0.0	0.0	0.0	0.0
200	75	0.0	0.0	0.0	0.0	0.0
270	53	0.0	0.0	0.0	0.0	0.0
325	45	0.0	0.0	0.0	0.0	0.0
400	38	0.0	0.0	0.0	0.0	0.0
Pan		0.0	0.0	0.0	0.0	0.0
Mean Particle Size (μm)		490 – 520				
Bulk Density (g/cm ³)						
Loose		1.6	1.5	1.4	1.5	1.4
Packed		1.8	1.7	1.7	1.7	1.7

Table 5-4. Summary of Metals Content in the Fluid Bed Reactor Bed Media

Metals Concentration (mg/kg)								Bed/Waste ^a Metal Ratio
Waste Feed	Starting Bed	Bed Media						
		End of Run #1	Grab Sample		End of Run #3	Composite End of Run #3		
			End of Run #2					
RCRA Metals ^b								
Arsenic	90	< 0.5	< 0.5	0.9	< 0.5	3.7	82	
Beryllium	< 50	< 50	< 50	50	< 50	< 50	NA	
Cadmium	990	< 10	190	160	120	80	8	
Chromium	1,100	170	560	790	1,280	1,350	7	
Antimony	380	< 50	< 50	200	< 50	70	4	
Barium	1,250	< 50	570	830	1,520	1,480	24	
Lead	320	50	130	180	240	260	16	
Silver	8	< 2	< 2	3.1	2.2	< 2	NA	
Other Parameters ^b								
Aluminum	3,800	300	800	1,400	1,900	1,700	1	
Calcium	1,000	110	560	800	1,370	1,280	12	
Carbon	NM	< 100	1,000	400	200	600	NA	
Copper	65	20	30	50	60	50	38	
Iron	1,680	1,105	1,810	2,520	3,030	3,050	2	
Magnesium	245	50	310	460	810	750	61	
Nickel	< 10	< 10	20	20	20	20	NA	
Phosphorus	< 10	< 10	50	40	70	60	> 600	
Potassium	40	15	150	120	220	230	383	
Sodium	150	< 10	270	420	740	730	487	
Zinc	790	80	580	1,270	1,680	1,320	21	

NM - Not Measured

Notes:

a) The "Bed/Waste Metal Ratio" is calculated using the concentrations in the table as follows:

$$\text{Bed/Waste Metal Ratio} = (\text{Ending Bed}) / (\text{Starting Bed} / \text{Starting Waste})$$

This ratio provides a comparison of how much the concentration of each metal increased in the bed relative to the concentration of that metal in the starting waste. Larger numbers indicate a greater tendency for a metal to remain in the bed.

b) Mercury, thallium, chlorides, and selenium were determined to be nondetect in all samples.

Table 5-5. Summary of Fluid Bed Reactor CEMS Data

Test Parameter	Units	Test Run #1			Test Run #2			Test Run #3		
		Case 1A	Case 1B	Case 1C	Case 2A	Case 2B	Case 2C	Case 3A	Case 3B	Case 3C
FLUID BED REACTOR										
Bed Temperature	°C	779	780	775	879	877	876	965	967	965
Bed Gas Residence Time	s	1.8	1.8	1.7	1.8	1.8	1.8	1.5	1.5	1.6
Freeboard Temperature	°C	798	730	760	842	795	817	850	865	871
Freeboard Gas Residence Time	s	1.7	1.8	1.9	1.9	2.0	2.0	2.0	1.8	2.1
Average Combustion Temperature	°C	788	755	767	860	834	845	899	911	912
STACK EMISSIONS										
Oxygen (O ₂)	vol % ^a	5.7	7.1	9.4	5.8	7.0	9.1	5.1	7.0	6.9
Carbon Dioxide (CO ₂)	vol % ^a	13.3	12.0	10.1	13.1	12.2	10.2	13.7	11.6	9.8
Carbon Monoxide (CO)	ppm ^a	353	99	41	114	61	16	197	39	14
Oxides of Nitrogen (NO _x)	ppm ^a	416	515	630	593	665	751	672	606	656
Sulfur Dioxide (SO ₂)	ppm ^a	57	21	27	88	36	52	90	86	80
Total Hydrocarbons (THC)	ppm ^a	21	7	1.4	NM	NM	NM	9	4	3
Conversion										
Waste Nitrogen to NO _x Nitrogen	mass %	NM	2.5	NM	NM	3.5	NM	NM	3.8	NM
Waste Sulfur to SO ₂ Sulfur	mass %	NM	27.2	NM	NM	51.1	NM	NM	113.8	NM

Notes:
a) Measured on a dry volume basis.
b) NM - Not Measured or Not Monitored

Table 5-6. Summary of Pilot Test Emissions

Compound	Units ^a	Pilot Test Run		
		#1	#2	#3
Bed Temperature	°C	778	877	966
Offgas Oxygen	mol %	7.1	7.0	7.0
Offgas Flow Rate	m ³ /min	1.37	1.40	1.37
Volatile Organics				
Chloromethane	µg/m ³	42	19	23
Acrylonitrile	µg/m ³	43	11	ND
Benzene	µg/m ³	274	160	212
Toluene	µg/m ³	17	8	5
Styrene	µg/m ³	6	4	2
Semivolatile Organics				
Phenol	µg/m ³	63	81	36
Napthalene	µg/m ³	65	380	46
Di-n-butylphthalate	µg/m ³	54	2	4
bis(2-Ethylhexyl)phthalate	µg/m ³	5,489	5,041	3,792
Metals				
Barium	µg/m ³	348	286	167
Lead	µg/m ³	510	235	438
Arsenic	µg/m ³	48	2	2
Cadmium	µg/m ³	1,107	1,864	2,729
Chromium	µg/m ³	125	96	53
Iron	µg/m ³	878	160	104
Potassium	µg/m ³	224	70	93
Sodium	µg/m ³	418	1,946	250
Zinc	µg/m ³	1,182	140	128
Miscellaneous Emissions				
Particulate	µg/m ³	19,226	18,067	17,372
HCl/Cl ₂ ^b	µg/m ³	53,799	57,011	54,965
Cyanides	µg/m ³	1,020	164	37
Total PCDD/PCDF	ng/m ³	40.2	6.5	8.8
TCDD Equivalent ^c	ng/m ³	0.64	0.12	0.14

Notes:

- Dry basis at standard conditions of 20°C (68°F) and 1 atmosphere. Concentrations have been corrected to 7 volume percent oxygen.
- Based on total chloride content of impinger solutions. Not differentiated for HCl and Cl₂.
- Based on USEPA 1989 toxicity equivalents factors.

Table 5-7. Summary of System Removal Efficiencies for Metals

Metal	Concentration of Metal in Feed (mg/kg)	Minimum System Removal Efficiency ^a		
		Test Run #1 (%)	Test Run #2 (%)	Test Run #3 (%)
NONCARCINOGENIC METALS				
Antimony	80	> 99.3184	> 99.3218	> 99.4042
Barium	1,250	> 99.9876	> 99.9882	> 99.9906
Lead	320	> 99.9488	> 99.9561	> 99.9517
Silver	8	> 99.3257	> 99.3278	> 99.4079
CARCINOGENIC METALS				
Arsenic	2	> 99.6237	> 99.9354	> 99.9418
Cadmium	985	> 99.9738	> 99.9621	> 99.9521
Chromium	1,100	> 99.9887	> 99.9890	> 99.9908
OTHER METALS				
Aluminum	3,750	> 99.9845	> 99.9839	> 99.9866
Calcium	1,000	> 99.9841	> 99.9800	> 99.9906
Copper	65	> 99.8309	> 99.8321	> 99.8513
Iron	1,680	> 99.9872	> 99.9922	> 99.9935
Magnesium	245	> 99.9498	> 99.9502	> 99.9569
Potassium	40	> 99.6876	> 99.7076	> 99.7331
Sodium	150	> 99.8883	> 99.8952	> 99.9032
Zinc	790	> 99.9676	> 99.9838	> 99.9858

Notes:

- a) Calculated assuming nondetect values are present at the analytical detection limits. Therefore, reported SRE's are minimum values.

Table 5-8. Comparison of Projected Full-Scale Emissions to Regulatory Limits

Compound	Units	Projected ^a Emissions	Regulatory Limits			
			Current		Potential	
			Value ^b	Source	Value ^b	Source
Volatile Organics						
Chloromethane	g/h	0.041	NA		2,333	BIF
Acrylonitrile	g/h	0.024	NA		125	BIF
Benzene	g/h	0.343	NA		1,000	Utah
Toluene	g/h	0.017	NA		250,000	BIF
Semivolatile Organics						
Phenol	g/h	0.175	NA		25,000	BIF
Napthalene	g/h	0.819	NA		83	BIF
Di-n-butylphthalate	g/h	0.004	NA		41,667	Utah
bis(2-Ethylhexyl)phthalate	g/h	10.8	NA		13,917	Utah
Metals						
Barium	g/h	0.070	41,667	BIF	41,667	BIF
Lead	g/h	0.068	75	BIF	75	BIF
Arsenic	g/h	0.001	1.9	BIF	1.9	BIF
Cadmium	g/h	0.121	4.7	BIF	4.7	BIF
Chromium	g/h	0.063	0.7	BIF	0.7	BIF
Miscellaneous Emissions						
Particulate ^c	µg/m ³	18,067	185,300	RCRA	11,581	CETRED
HCl/Cl ₂ ^d	g/h	113.5	1,816	RCRA	333	BIF
Cyanides	g/h	0.314	NA		16,667	BIF
Total PCDD/PCDF ^c	ng/m ³	6.5	NA		5.4 – 9.7	CETRED
TCDD Equivalent ^{c, e}	ng/m ³	0.12	NA		0.12 – 0.17	CETRED

NA - Not Applicable
BIF - Boiler and Industrial Furnace Regulations (40 CFR 266)
Utah - State of Utah Air Toxics Policy
RCRA - 40 CFR 264 (Subpart O, Incinerator Regulations)
CETRED - Combustion Emission Technical Resource Document

Notes:

- Projected emissions were estimated by scaling the pilot test emissions from Test Run #2 to a 227 kg/h full-scale system.
- Regulatory limits with a "BIF" or "Utah" source were calculated from applicable ground level standards using a site specific dispersion factor of 0.0012 (µg/m³)/(g/h).
- Dry basis at standard conditions of 20°C (68°F) and 1 atmosphere. Concentrations have been corrected to 7 mole percent oxygen.
- Based on total chloride content of impinger solutions. The emissions were not differentiated for HCl and Cl₂. The potential regulatory limit is the more stringent value for chlorine.
- Based on USEPA 1989 toxicity equivalents factors.

Table 5-9. Ash Particle Size Distribution - Dry Screen Analysis

Sieve Size		Cumulative Mass Percent Passing					
		Cyclone Catch			Baghouse Catch		
mesh	μm	9/14/94	9/15/94	9/16/94	9/14/94	9/15/94	9/16/94
20	850	99.9	100.0	99.8	100.0	100.0	100.0
28	600	85.6	95.8	89.3	100.0	100.0	100.0
35	425	67.4	73.0	44.0	100.0	100.0	100.0
48	300	58.7	66.4	31.7	97.5	99.6	98.8
65	212	57.5	65.8	30.6	80.1	82.7	75.5
100	150	55.6	63.9	28.3	54.6	55.5	46.6
150	106	52.5	60.2	25.4	26.6	41.8	32.7
200	75	43.2	52.3	20.8	11.9	23.1	20.9
270	53	39.4	47.8	17.5	4.6	8.3	9.2
325	45	33.1	42.3	15.1	1.5	2.4	2.9
400	38	26.1	36.9	12.6	1.3	1.4	0.9
Pan		0.0	0.0	0.0	0.0	0.0	0.0
Mean Particle Size (μm)		95 - 100	65 - 70	450 - 460	135 - 140	135 - 140	160 - 170
Bulk Density (g/cm^3)							
Loose		1.05	0.98	1.35	0.27	0.30	0.27
Packed		1.51	1.43	1.70	0.42	0.40	0.39

Table 5-10. Ash Particle Size Distribution - Bahco Microparticle Size Analysis

Sieve Size		Cumulative Mass Percent Passing	
		Cyclone Catch Composite Sample	Baghouse Cleanout Sample
mesh	μm		
100	149	62.5	87.5
200	74	55.8	87.3
400	37	47.0	87.2
	30.4	43.6	87.1
	24.8	42.0	87.0
	18.8	38.9	86.9
	11.7	30.2	86.5
	7.8	21.1	85.7
	3.9	11.2	71.0
	2	2.9	41.1
	1.3	1.1	20.0
Mean Particle Size (μm)		55 - 60	2 - 3

Table 5-11. Summary of Ash Metal Analytical Results - Fluid Bed Reactor Pilot Test

Metal Analyte	Metals Concentration (mg/kg)										
	Waste Feed	Ash from Muffle Roasted Waste	Test Run #1 Bed Temperature = 776 Deg C			Test Run #2 Bed Temperature = 876 Deg C			Test Run #3 Bed Temperature = 966 Deg C		
			Cyclone Ash	Baghouse Dust	Cyclone Ash	Baghouse Dust	Cyclone Ash	Baghouse Dust	Cyclone Ash	Baghouse Dust	
RCRA Metals											
Arsenic	2	9	4.2	41	9.0	67	5.4	94			
Beryllium	< 50	< 50	< 50	< 50	< 50	< 50	< 50	< 50			
Cadmium	985	5,000	9,200	67,800	11,500	94,100	6,620	137,000			
Chromium	1,100	24,450	19,400	16,800	24,300	15,800	12,800	14,400			
Antimony	80	325	70	310	70	280	< 50	320			
Barium	1,250	28,700	19,200	27,300	22,800	25,400	11,100	20,000			
Lead	320	4,760	2,530	8,840	3,690	13,900	1,730	22,200			
Mercury	< 0.1	< 0.1	< 0.1	3.8	< 0.1	4.6	< 0.1	2.3			
Silver	8	123	64	110	59	300	37	833			
Thallium	< 50	< 50	< 50	< 50	< 50	< 50	< 50	< 50			
Other Metals/Anions											
Aluminum	3,750	29,500	17,700	17,000	19,800	16,700	11,200	19,700			
Calcium	1,000	26,750	19,800	16,100	16,800	14,000	10,200	11,100			
Carbon	475,400	NM	4,400	26,500	3,600	23,300	3,200	33,600			
Chloride	800	NM	800	29,900	1,200	44,200	700	77,900			
Copper	65	1,175	660	790	680	1,020	370	1,300			
Iron	1,680	30,800	23,700	31,100	25,300	20,500	15,600	17,500			
Magnesium	245	17,900	13,300	10,800	14,500	10,800	7,950	8,560			
Nickel	< 10	130	140	160	150	140	120	140			
Phosphorus	< 10	762	260	< 10	1,470	< 10	130	590			
Potassium	40	4,445	2,660	4,090	2,660	4,900	1,340	5,900			
Selenium	< 0.5	< 0.5	< 0.5	1.6	< 0.5	0.6	< 0.5	0.5			
Silicon	7,350	128,000	249,000	99,400	215,000	102,000	310,000	87,800			
Sodium	150	1,275	8,670	7,940	6,270	10,800	3,220	13,800			
Sulfate	NM	25,000	9,700	20,600	7,600	26,200	4,100	36,700			
Zinc	790	18,050	6,420	16,400	8,360	15,300	3,090	12,900			

Notes:
a) Waste plastic ash was muffle roasted at 900 °C.

Table 5-12. Ratio of Baghouse/Cyclone Ash Concentrations ^a

Analyte	Pilot Test Run			Average
	#1	#2	#3 ^b	
Chloride	37.4	36.8	111.3	61.8
Mercury	38.0	46.0	23.0	35.7
Cadmium	7.4	8.2	20.7	12.1
Arsenic	9.8	7.4	17.4	11.5
Silver	1.7	5.1	22.3	9.7
Lead	3.5	3.8	12.8	6.7
Antimony	4.4	4.0	6.4	4.9
Zinc	2.6	1.8	4.2	2.9
Potassium	1.5	1.8	4.4	2.6
Sodium	0.9	1.7	4.3	2.3
Copper	1.2	1.5	3.5	2.1
Barium	1.4	1.1	1.8	1.4
Iron	1.3	0.8	1.1	1.1
Nickel	1.1	0.9	1.2	1.1
Aluminum	1.0	0.8	1.2	1.0
Magnesium	0.8	0.7	1.2	0.9
Calcium	0.8	0.8	1.1	0.9
Chromium	0.9	0.7	1.1	0.9

Notes:

- Ratios were calculated by dividing the concentration of the metal in the baghouse dust by the concentration of the metal in the cyclone ash.
- The ratios are higher in Test Run #3 due to the dilutional effect of the increased bed carryover on the metals concentrations in the cyclone ash.

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Table 6-1. Ash Composite Mass Distribution

Test Number and Date	Mass Percentages of FBR Ash		
	Cyclone, %	Baghouse, %	Total, %
Test 1; September 14, 1994	27.45	1.13	28.58
Test 2; September 15, 1994	27.70	0.76	28.46
Test 3; September 16, 1994	39.34	0.79	40.13
Baghouse Cleanout	0.00	2.83	2.83
Total	94.49	5.51	100.00

Table 6-2. Summary of Ash Stabilization Data

Metal Analyte	Ash Composite Total Metals (mg/kg)	Ash Composite	TCLP Values (mg/l)						Regulatory Limit	
			Sample Number							
			#1	#2	#3	#4	#5	#6		
Arsenic	11	< 0.2	< 0.29	< 0.58	< 0.58	< 0.58	< 0.58	< 0.58	5.0	
Barium	22,877	0.8	1.2	1.2	1.2	2.6	2.2	1.8	100.0	
Cadmium	13,942	288	140	< 0.025	0.03	< 0.025	< 0.025	< 0.025	1.0	
Chromium	24,049	32.5	0.16	9.9	0.12	2.2	0.52	0.22	5.0	
Lead	3,992	< 0.5	400	0.28	0.30	0.32	< 0.28	< 0.28	5.0	
Mercury	< 0.2	< 0.0001	0.0003	0.0003	0.0003	< 0.0002	0.0002	< 0.0002	0.2	
Selenium	< 1	< 0.03	< 0.5	< 0.36	< 0.71	< 0.71	< 0.71	< 0.71	5.0	
Silver	66	< 0.03	< 0.36	< 0.50	< 0.50	< 0.50	< 0.50	< 0.50	1.0	
Stabilization Sample Mixture Components (g/100 g of ash)										
Type II Portland Cement			30	25	28.6	4.3	10	40		
Fly Ash			0	5	7.1	0	0	0		
Blast Furnace Slag			0	0	0	38.5	90	360		
Sodium Sulfide			0	0	7.1 ^a	0	0	0		
Water			41.5	41.5	48.4 ^b	42.1	60	147.5		
Bulking Factor (g mix/g of ash) ^c			1.7	1.7	1.9	1.8	2.6	6.5		

Notes:

- Sodium Sulfide (Na₂S) was added as Na₂S • 9H₂O. The mass reported added is minus the water.
- The mass of water reported includes the chemically bound water from the Na₂S.
- The mass of mix includes water added to the mix.
- Shaded values indicate the TCLP results were greater than the regulatory limit.

Table 6-3. Analytical Results of Stabilizing Agents

Analysis ^a	Fly Ash	Blast Furnace Slag
Major Metals (mass %)		
Aluminum (Al ₂ O ₃)	22.40	7.62
Barium (BaO)	0.49	0.04
Calcium (CaO)	17.80	37.95
Chlorine	< 0.02	0.05
Iron (Fe ₂ O ₃)	3.28	0.38
Magnesium (MgO)	5.47	11.95
Manganese (MnO)	0.13	0.62
Phosphorous (P ₂ O ₅)	0.58	< 0.05
Potassium (K ₂ O)	0.43	0.44
Silicon (SiO ₂)	45.35	37.90
Sodium (Na ₂ O)	1.22	0.24
Sulfur (SO ₃)	1.51	2.86
Titanium (TiO ₂)	1.06	0.46
Total (mass %)	99.72	100.51
Trace Metals (mg/kg)		
Arsenic	37	< 20
Chromium	65	26
Cobalt	< 10	< 10
Copper	124	< 10
Lead	77	21
Molybdenum	17	< 10
Niobium	23	23
Nickel	27	< 10
Rubidium	26	24
Strontium	4,803	396
Tin	143	< 50
Thorium	36	< 10
Tungsten	< 10	< 10
Uranium	36	< 10
Vanadium	74	32
Yttrium	48	41
Zinc	44	27
Zirconium	376	524

Notes:

a) Results were determined by SRF spectrographic scan.

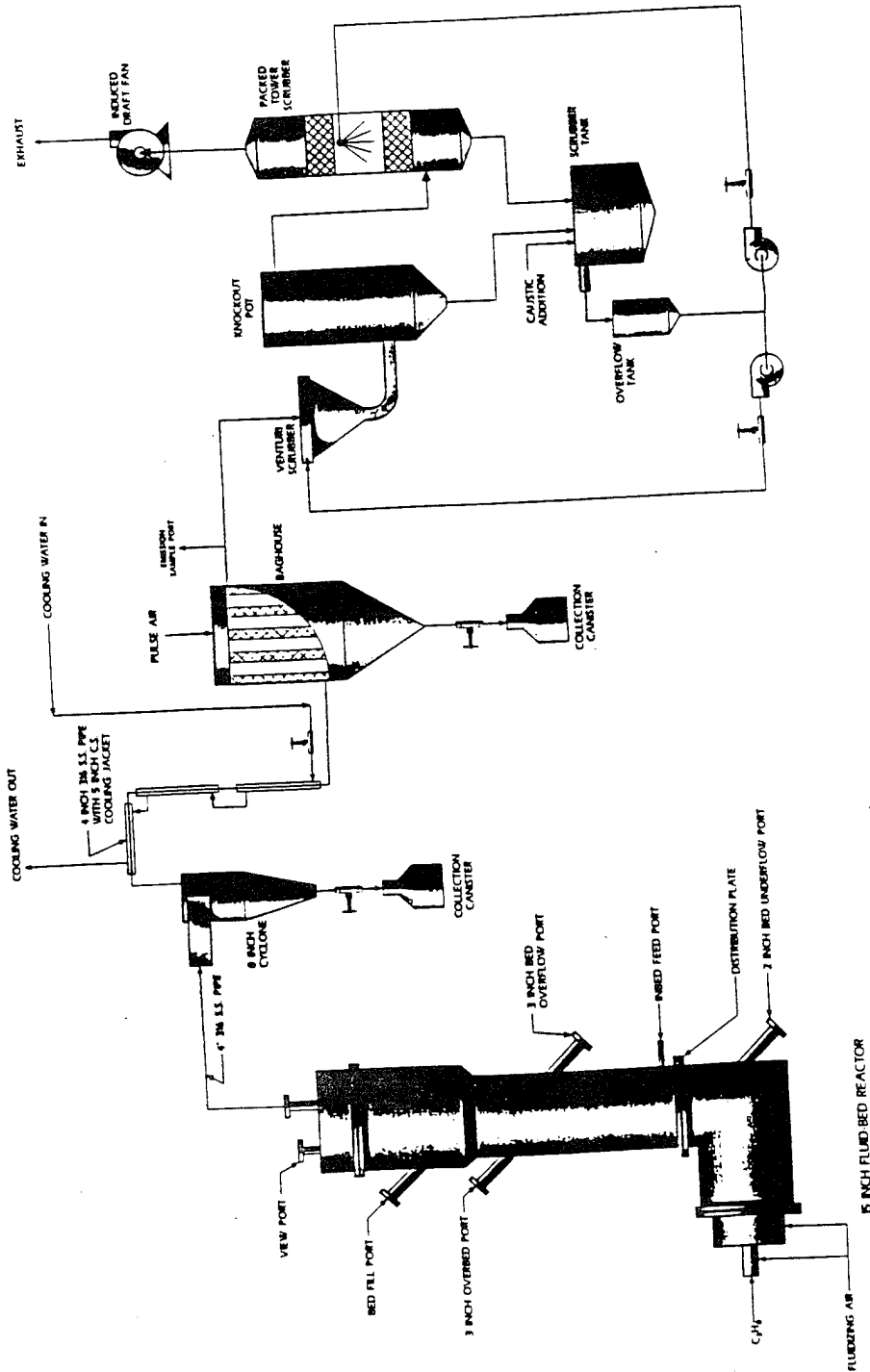


Figure 1. Flow Diagram for Fluid Bed Reactor Pilot Test Process

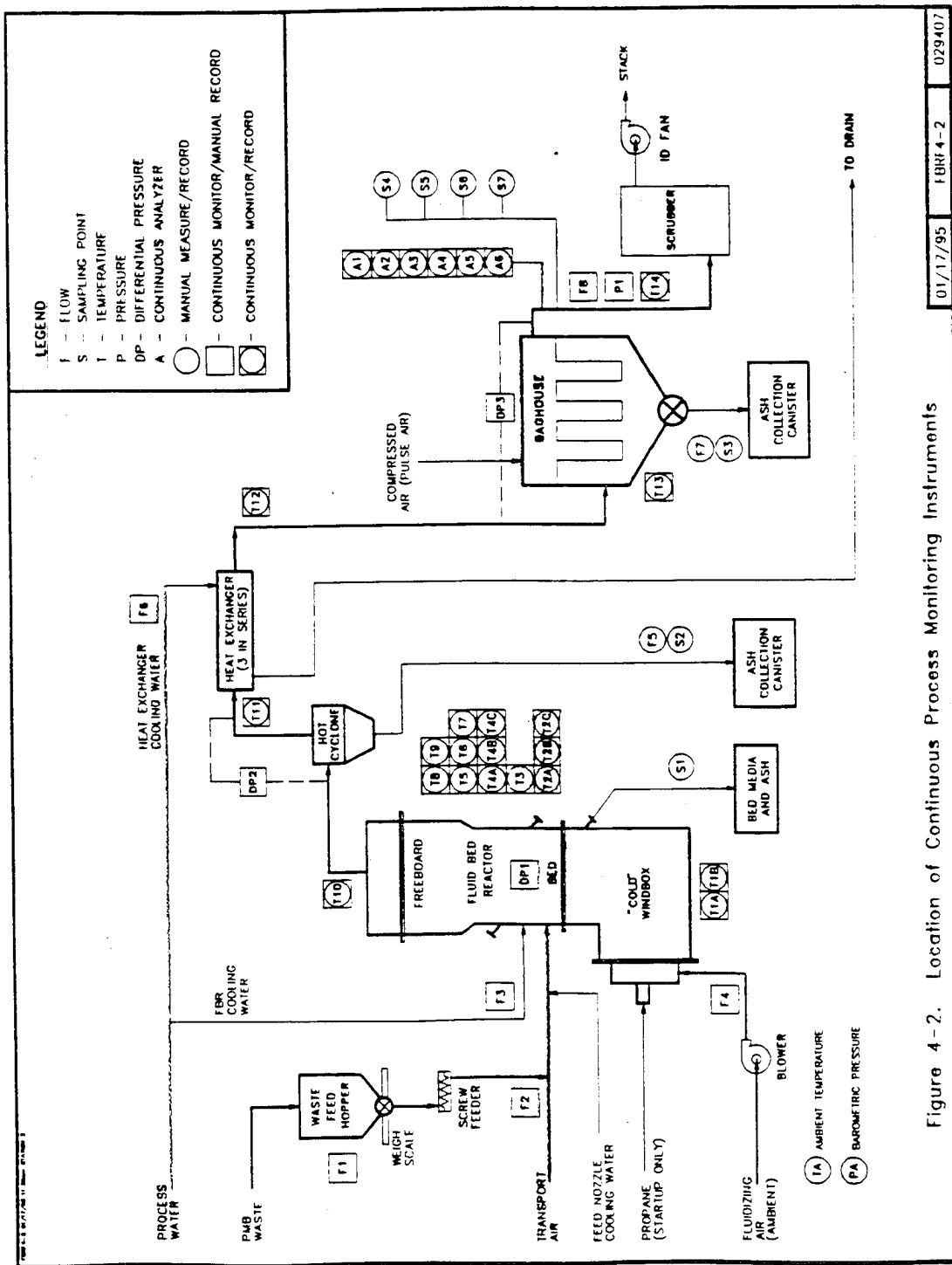


Figure 4-2. Location of Continuous Process Monitoring Instruments

Figure 5-1. Offgas CO vs Offgas Oxygen Concentration

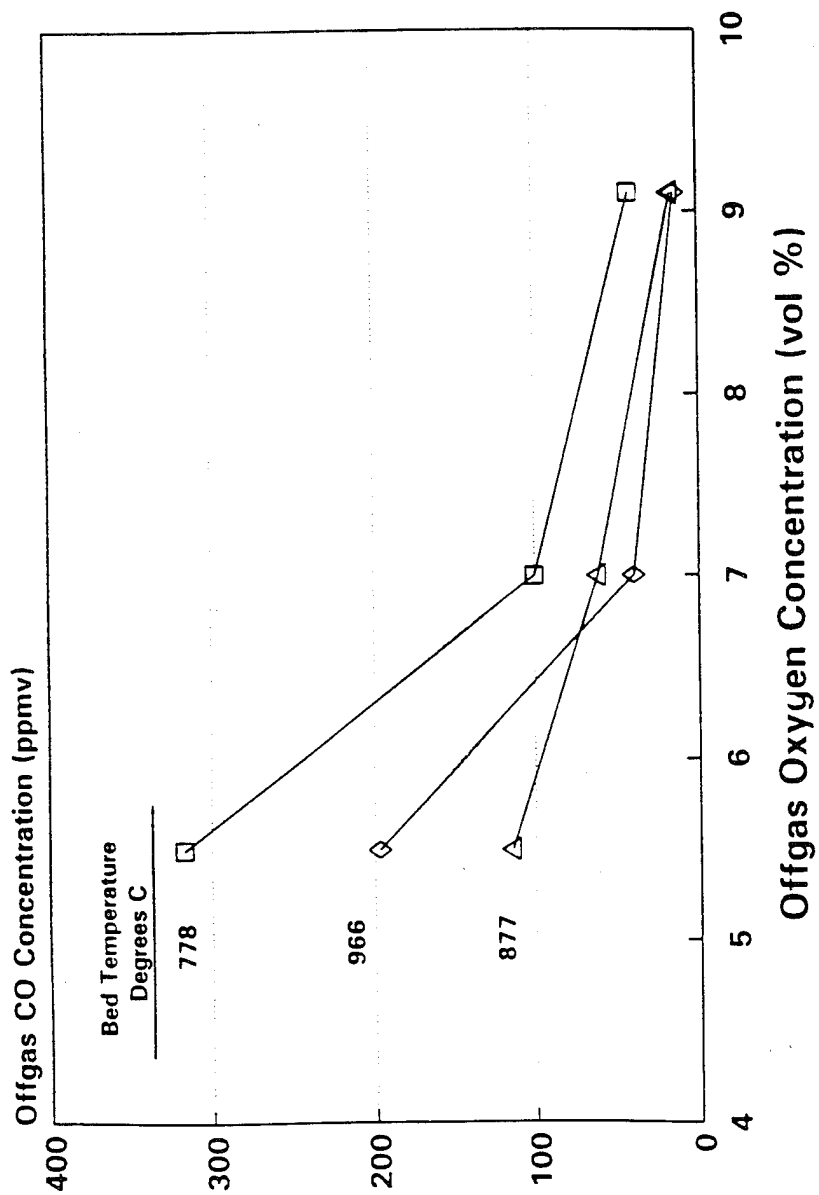
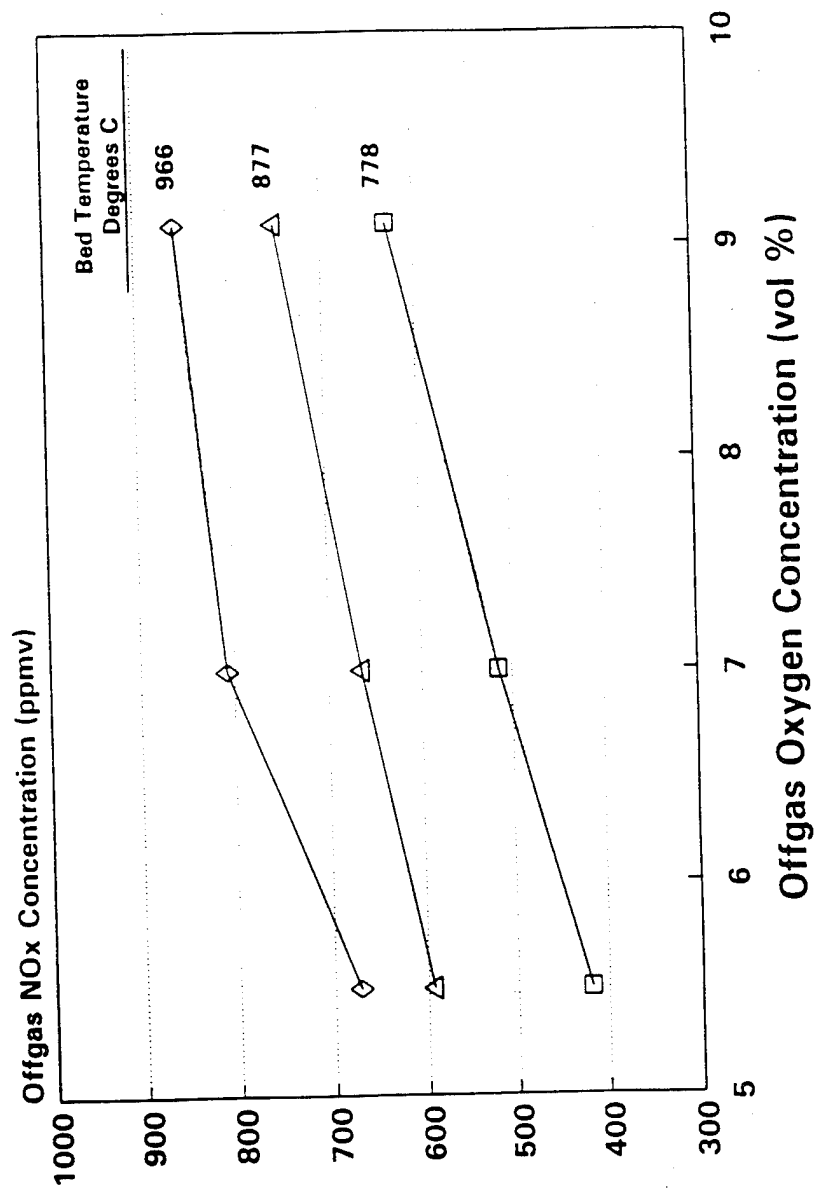


Figure 5-2. Offgas NOx vs Offgas Oxygen Concentration



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Annex 1
Bench-Scale Test Equipment Photographs

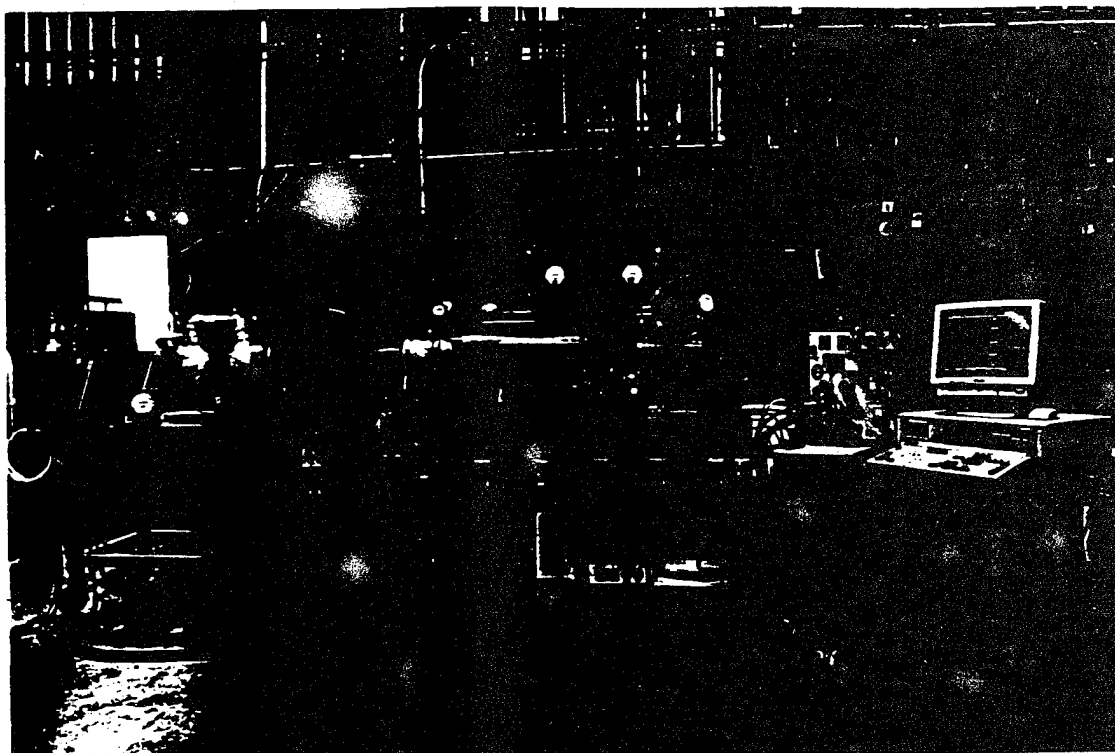


Figure 5. Four-inch-diameter Batch Kiln System

The batch kiln system used for this study was comprised of an electrically heated furnace which housed the quartz kiln (right center of photo), followed by an electrically heated afterburner (left center of photo), and the gas sampling system. The Nomex filter and impinger train are shown on the far left of the photo. The gas meter and vacuum pump shown on the right were used to measure the system flow rates and to control system pressures.

Auxiliary equipment used in the process included the CEM and a data acquisition system (not shown). Data was transmitted from the CEM through the data acquisition system to the computer shown on the far right of the photo. A software program was used to record the data on 30-second intervals, and the data trends were shown graphically on the terminal.

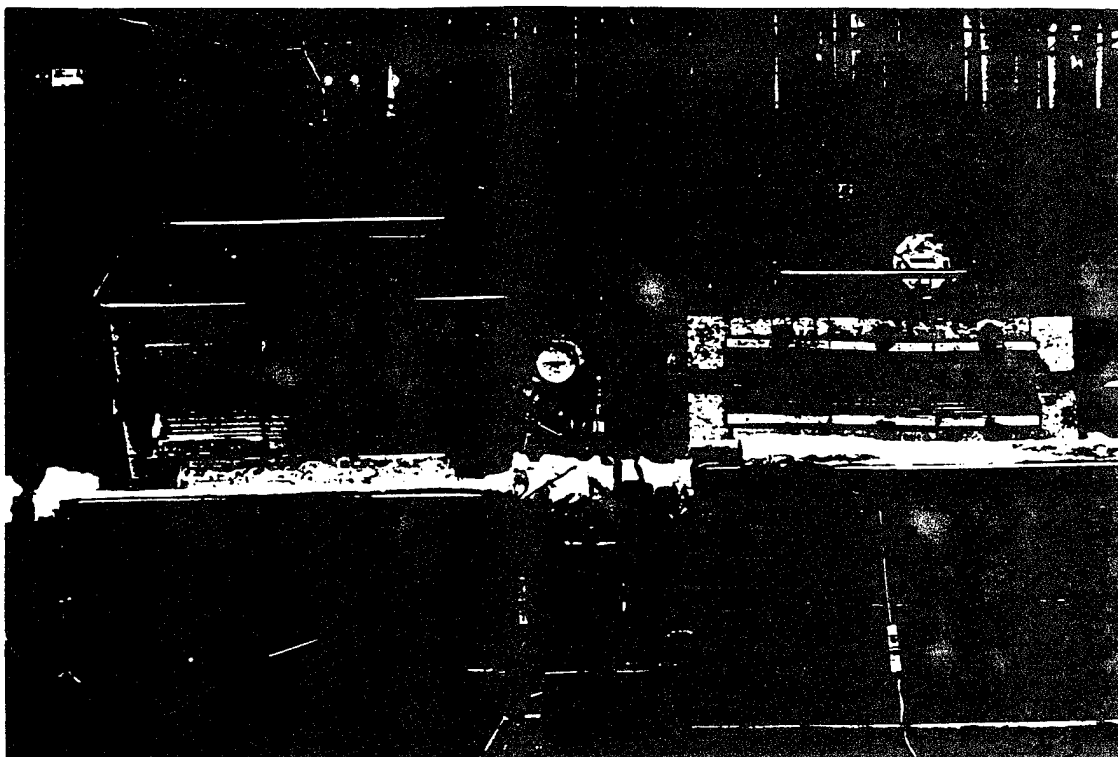


Figure 6. Four-inch-diameter Batch Kiln and Afterburner

This photograph provides a close-up view of the batch kiln and afterburner that were used in the testing. Both the kiln (on the right of the photo) and the afterburner (left) were constructed of quartz. The afterburner contained quartz media (0.75 inch outside diameter by 0.75 inch long) to provide mixing of the volatile matter and air to enhance the combustion of volatiles.

Air was introduced into the afterburner at the connecting points between the kiln and the afterburner. The connecting port was heat-traced and insulated to reduce the potential for condensation of volatiles in that area. A thermocouple was positioned between the kiln and afterburner to record the gas stream temperature between the two units.

The afterburner was operated at a temperature of about 1000°C for the purpose of effectively combusting the volatile matter that was carried in the gas stream from the kiln. The orange glow emanating from the afterburner is the result of the electrical heat that is provided to attain the required temperature.

Metal Constituents Mass Balance – Test Run #3

Metal Analyte	Test Material (mg)	Kiln Ash (mg)	Kiln Wash (mg)	Nomex Filter (mg)	APC Wash (mg)	Particulate Filter (mg)	Impinger Solution (mg)	Total Metals Accountable (mg)	Recovery ^a (wt%)	SRE (wt%)
Antimony	12.0	0.55	< 2.5	< 0.05	< 0.54	< 0.05	< 2.05	< 5.74	ID	ID
Arsenic	0.080	0.035	0.023	0.004	0.003	0.0023	0.009	0.07	ID	82.0
Barium	46.5	38.1	2.0	< 0.005	< 0.11	0.003	< 0.41	40.7	87	> 98.7
Beryllium	< 2.0	< 0.020	< 0.50	< 0.005	< 0.11	< 0.005	< 0.41	< 1.05	ID	ID
Cadmium	1.4	0.1	< 0.5	0.447	< 0.11	< 0.005	< 0.41	< 1.53	ID	ID
Chromium	62.6	47.7	1.0	0.028	< 0.11	0.004	< 0.41	49.3	79	> 98.9
Lead	49.6	50.0	2.5	0.064	< 0.11	0	< 0.41	53.1	107	> 99.0
Mercury	0.040	0.002	NA	NA	NA	NA	NA	NA	ID	ID
Selenium	< 0.10	0.001	< 0.03	< 0.0005	< 0.005	< 0.0005	< 0.02	< 0.05	ID	ID
Silver	< 0.34	< 0.003	< 0.25	< 0.005	< 0.05	< 0.005	< 0.21	< 0.5	ID	ID
Thallium	< 2.0	< 0.10	< 0.50	< 0.1	< 0.11	< 0.1	< 0.41	< 1.3	ID	ID

Notes:

- a) If the metals concentrations in the starting test material was at or near the analytical detection limit, quantitative determinations of recovery are not accurate and have been listed as "ID" for insufficient data.

Metal Analytical Results - Test Run #3

Metal Analyte	Test Material (mg/kg)	Kiln Ash (mg/kg)	Kiln Wash (mg/l)	Nomex Filter (mg)	Nomex Blank (mg)	Particulate Filter (mg)	Particulate Blank (mg)	APC Wash (mg/l)	Impinger Solution (mg/l)	Impinger Blank (mg/l)
Mass (gm)	200	2.04		4.8981	4.8595	0.6183	0.6126			
Volume (liters)			0.500					0.108	0.41	0.3
Antimony	60	270	< 5	< 0.05	< 0.05	< 0.05	< 0.05	< 5	< 5	< 5
Arsenic	0.4	17.2	0.045	0.0047	0.0008	0.004	0.0017	0.024	0.021	< 0.005
Barium	233	18,700	4.0	< 0.005	0.012	0.125	0.122	< 1	< 1	< 1
Beryllium	< 10	< 10	< 1	< 0.005	< 0.005	< 0.005	< 0.005	< 1	< 1	< 1
Cadmium	7	30	< 1	0.452	< 0.005	< 0.005	< 0.005	< 1	< 1	< 1
Chromium	313	23,400	2.0	0.044	0.016	0.044	0.04	< 1	< 1	< 1
Lead	248	24,500	5.0	0.084	< 0.02	0.032	0.032	< 1	< 1	< 1
Mercury	0.2	1.2	NA	NA	NA	NA	NA	NA	NA	NA
Selenium	< 0.5	0.7	< 0.05	< 0.0005	< 0.0005	< 0.0005	< 0.0005	< 0.05	< 0.05	< 0.05
Silver	< 1.7	< 1.7	< 0.5	< 0.005	< 0.005	< 0.005	< 0.005	< 0.5	< 0.5	< 0.5
Thallium	< 10	< 50	< 1	< 0.1	< 0.1	< 0.1	< 0.1	< 1	< 1	< 1

Metal Constituents Mass Balance – Test Run #2

Metal Analyte	Test Material (mg)	Kiln Ash (mg)	Kiln Wash (mg)	Nomex Filter (mg)	APC Wash (mg)	Particulate Filter (mg)	Impinger Solution (mg)	Total Metals Accountable (mg)	Recovery ^a (wt%)	SRE (wt%)
Antimony	12.0	0.40	< 2.5	< 0.05	< 0.40	< 0.05	< 2.00	< 5.42	ID	ID
Arsenic	0.080	0.030	0.042	0.015	0.005	0.0067	0.03	0.13	ID	67.8
Barium	46.5	36.6	2.0	< 0.005	< 0.08	0.002	< 0.40	39.1	84	> 98.8
Beryllium	< 2.0	< 0.018	< 0.50	< 0.005	< 0.08	< 0.005	< 0.40	< 1.01	ID	ID
Cadmium	1.4	0.2	< 0.5	0.267	< 0.08	0.003	< 0.40	< 1.44	ID	ID
Chromium	62.6	35.9	1.5	0.004	< 0.08	0	< 0.40	37.9	61	> 98.7
Lead	49.6	47.1	1.5	< 0.02	< 0.08	< 0.02	< 0.40	49.1	99	> 99.0
Mercury	0.040	0.003	NA	NA	NA	NA	NA	NA	ID	ID
Selenium	< 0.10	0.003	< 0.03	< 0.0005	< 0.004	< 0.0005	< 0.02	< 0.05	ID	ID
Silver	< 0.34	< 0.003	< 0.25	< 0.005	< 0.04	< 0.005	< 0.20	< 0.5	ID	ID
Thallium	< 2.0	< 0.09	< 0.50	< 0.1	< 0.08	< 0.1	< 0.40	< 1.3	ID	ID

Notes:

- a) If the metals concentrations in the starting test material was at or near the analytical detection limit, quantitative determinations of recovery are not accurate and have been listed as "ID" for insufficient data.

Metal Analytical Results - Test Run #2

Metal Analyte	Test Material (mg/kg)	Kiln Ash (mg/kg)	Kiln Wash (mg/l)	Nomex Filter (mg)	Nomex Blank (mg)	Particulate Filter (mg)	Particulate Blank (mg)	APC Wash (mg/l)	Impinger Solution (mg/l)	Impinger Blank (mg/l)
Mass (gm)	200	1.84		4.9859	4.9449	0.6134	0.6113			
Volume (liters)			0.504					0.08	0.4	0.3
Antimony	60	220	< 5	< 0.05	< 0.05	< 0.05	< 0.05	< 5	< 5	< 5
Arsenic	0.4	16.2	0.084	0.0156	0.0008	0.0084	0.0017	0.062	0.074	< 0.005
Barium	233	19,900	4.0	< 0.005	0.012	0.124	0.122	< 1	< 1	< 1
Beryllium	< 10	< 10	< 1	< 0.005	< 0.005	< 0.005	< 0.005	< 1	< 1	< 1
Cadmium	7	100	< 1.0	0.272	< 0.005	0.008	< 0.005	< 1	< 1	< 1
Chromium	313	19,500	3.0	0.02	0.016	0.036	0.04	< 1	< 1	< 1
Lead	248	25,600	3.0	< 0.02	< 0.02	< 0.02	0.032	< 1	< 1	< 1
Mercury	0.2	1.8	NA	NA	NA	NA	NA	NA	NA	NA
Selenium	< 0.5	1.7	< 0.05	< 0.0005	< 0.0005	< 0.0005	< 0.0005	< 0.05	< 0.05	< 0.05
Silver	< 1.7	< 1.7	< 0.5	< 0.005	< 0.005	< 0.005	< 0.005	< 0.5	< 0.5	< 0.5
Thallium	< 10	< 50	< 1	< 0.1	< 0.1	< 0.1	< 0.1	< 1	< 1	< 1

Metal Constituents Mass Balance – Test Run #1

Metal Analyte	Test Material (mg)	Kiln Ash (mg)	Kiln Wash (mg)	Nomex Filter (mg)	APC Wash (mg)	Particulate Filter (mg)	Impinger Solution (mg)	Total Metals Accountable (mg)	Recovery ^a (wt%)	SRE (wt%)
Antimony	12.0	0.94	< 2.4	< 0.05	< 0.53	< 0.05	< 2.13	< 5.79	ID	ID
Arsenic	0.080	0.066	0.061	0.107	0.04	0.0243	0.07	0.37	ID	63.5
Barium	46.5	34.4	1.4	0.002	< 0.17	0	< 0.43	36.5	78	> 98.4
Beryllium	< 2.0	< 0.016	< 0.48	< 0.005	< 0.17	< 0.005	< 0.43	< 1.10	ID	ID
Cadmium	1.4	0.3	0.5	0.027	< 0.17	< 0.005	< 0.43	< 1.40	ID	ID
Chromium	62.6	29.8	1.0	0.019	< 0.17	0	< 0.43	31.4	50	> 98.1
Lead	49.6	41.7	1.4	< 0.02	< 0.17	0	< 0.43	43.7	88	> 98.7
Mercury	0.040	0.004	NA	NA	NA	NA	NA	NA	ID	ID
Selenium	< 0.10	0.002	< 0.02	< 0.0005	< 0.01	< 0.0005	0.06	< 0.09	ID	ID
Silver	< 0.34	< 0.003	< 0.24	< 0.005	< 0.08	< 0.005	< 0.21	< 0.5	ID	ID
Thallium	< 2.0	< 0.08	0.96	< 0.1	< 0.17	< 0.1	< 0.43	< 1.8	ID	ID

Notes:

a) If the metals concentrations in the starting test material was at or near the analytical detection limit, quantitative determinations of recovery are not accurate and have been listed as "ID" for insufficient data.

Metal Analytical Results - Test Run #1

Metal Analyte	Test Material (mg/kg)	Kiln Ash (mg/kg)	Kiln Wash (mg/l)	Nomex Filter (mg)	Nomex Blank (mg)	Particulate Filter (mg)	Particulate Blank (mg)	APC Wash (mg/l)	Impinger Solution (mg/l)	Impinger Blank (mg/l)
Mass (gm)	200	1.64		5.0477	5.0409	0.6135	0.6114			
Volume (liters)			0.480					0.165	0.425	0.3
Antimony	60	210	< 5	< 0.05	< 0.05	< 0.05	< 0.05	< 5	< 5	< 5
Arsenic	0.4	40.1	0.128	0.108	0.0008	0.026	0.0017	0.24	0.167	< 0.005
Barium	233	21,000	3.0	0.015	0.012	0.117	0.122	< 1	< 1	< 1
Beryllium	< 10	< 10	< 1	< 0.005	< 0.005	< 0.005	< 0.005	< 1	< 1	< 1
Cadmium	7	180	1.0	0.032	< 0.005	< 0.005	< 0.005	< 1	< 1	< 1
Chromium	313	18,200	2.0	0.036	0.016	0.032	0.04	< 1	< 1	< 1
Lead	248	25,400	3.0	< 0.02	< 0.02	0.028	0.032	< 1	< 1	< 1
Mercury	0.2	2.7	NA	NA	NA	NA	NA	NA	NA	NA
Selenium	< 0.5	1.2	< 0.05	< 0.0005	< 0.0005	< 0.0005	< 0.0005	< 0.05	0.13	< 0.05
Silver	< 1.7	< 1.7	< 0.5	< 0.005	< 0.005	< 0.005	< 0.005	< 0.5	< 0.5	< 0.5
Thallium	< 10	< 50	2.0	< 0.1	< 0.1	< 0.1	< 0.1	< 1	< 1	< 1

Annex 6
Test Metal Analytical Results and Calculations

EPA EMISSION TEST DATA

Project Number 8184 Method Modified Method 5 Installation Batch Kiln

Date 10/26/93

Test Condition Test 3 Sample Location After Burner

Barometric Pressure: (Pb) 25.02 "Hg

Static Pressure: (Ps) 0 "H₂O

Absolute Pressure: (Pa) 25.02 "Hg

Pa = Pb + Ps/13.6

Nozzle Size (inch) 0.5

Impinger Train Weights (grams)

	#1	#2	#3	#4	SUM
Gross	666.0	643.0	496.4	909.7	2715.1
Tare	599.3	619.2	493.0	869.9	2581.4
Net Gain	66.7	23.8	3.4	39.8	133.7
Vws =	6.293	SCF			

Sample Point	Time	Pitot Tube		(Pm) H	Volume (ft ³)	Stack Temp. (Ts)	Oven Temp.	Last Impinger Temp.	Meter Temp (Tm)		Vacuum "Hg
		P	P						In	Out	
1	0855	-	-	0.91	215.85	88	316	48	64	64	4.0
2	0940	-	-	0.96	242.37	268	320	39	79	67	4.5
3	1025	-	-	0.96	269.20	275	322	39	81	71	4.5
4	1110	-	-	0.96	295.96	279	325	40	82	72	4.5
5	1155	-	-	1.00	323.19	279	323	40	83	73	5.0
6	1240	-	-	1.00	350.50	277	323	40	83	73	5.0
7	1325	-	-	1.00	378.07	275	326	41	83	74	5.0
8	1410	-	-	1.00	405.84	273	327	40	83	74	5.0
9	1440	-	-	1.00	424.24	270	328	41	83	74	4.5
10	1518	-	-	1.05	451.59	309	328	40	84	75	6.0
		Net		235.74	ft ³						
Total	383	0.00	0.00	9.84	2591.6						
Average				0.984	259						

Pm, "Hg abs = 25.09 Ts, °R = 719 Tm, °R = 536

Total SCF & ACF Sampled = 201.747 SCF 327.36 ACF

Total DSCF Samples = 195.453 DSCF

% Moisture = 3.12 %

Dust Concentration = 0.0035 gr/DSCF

Stack Gas Velocity, ft/sec = 0.00

Total Solid Sample Weight

	Filter Gross, g	Filter Tare, g	Filter Net, g
	4.8981	4.8595	0.0386
	0.0443	0.6183	0.6126
			0.0057

EPA EMISSION TEST DATA

Project Number 8184 Method Modified Method 5
 Date 10/22/93
 Test Condition Test 2 Installation Batch Kiln
 Sample Location After Burner

Barometric Pressure: (Pb) 24.90 "Hg
 Sample Location
 Static Pressure: (Ps) 0 "H₂O
 Absolute Pressure: (Pa) 24.9 "Hg
 Pa = Pb + Ps/13.6
 Nozzle Size (inch) 0.5
 Impinger Train Weights (grams)
 #1 #2 #3 #4 SUM
 Gross 670.6 644.4 496.6 883.2 2694.8
 Tare 599.0 618.4 493.7 846.1 2557.2
 Net Gain 71.6 26.0 2.9 37.1 137.6
 Vws = 6.477 SCF

Sample Point	Time	Pitot Tube		(Pm)	Volume (ft ³)	Stack Temp. (Ts)	Oven Temp.	Last Impinger Temp.	Meter Temp (Tm)		Vacuum "Hg
		P	P						In	Out	
1	0952	-	-	1.05	993.26	84	286	51	66	65	4.5
2	1037	-	-	1.02	1021.03	253	315	40	81	70	4.5
3	1122	-	-	1.02	1048.82	264	323	43	85	74	4.8
4	1207	-	-	1.04	1076.62	273	328	45	87	77	5.0
5	1222	-	-	1.04	1085.99	261	330	43	87	77	5.0
6	1252	-	-	1.08	1104.86	280	328	42	88	78	5.0
7	1337	-	-	1.08	1133.43	295	328	43	90	79	5.0
8	1422	-	-	1.10	1162.36	277	331	44	92	82	5.0
9	1507	-	-	1.02	1190.74	275	329	45	91	83	5.0
10	1543	-	-	1.40	1215.73	307	328	45	93	83	5.0
Total		351	0.00	10.85	Net 222.47 ft ³	2570			860	768	
Average				1.085		257			86	77	
				Pm, "Hg abs. = 24.98		Ts, °R = 717				Tm, °R = 541	

Total SCF & ACF Sampled = 188.303 SCF 306.10 ACF
 Total DSCF Samples = 181.826 DSCF
 % Moisture = 3.44 %
 Dust Concentration = 0.0037 gr./DSCF
 Stack Gas Velocity, ft/sec = 0.00 ft./sec.
 Total Solid Sample Weight
 Filter Gross, g 0.0431
 Filter Tare, g 0.6134
 Filter Net, g 0.6113
 Filter Net, g 0.0021

EPA EMISSION TEST DATA

Project Number 8184 Method Modified Method 5 Installation Batch Kiln

Date 10/21/93

Test Condition Test 1 Sample Location After Burner

Barometric Pressure: (Pb) 24.90 "Hg

Sample Location

Static Pressure: (Ps) 0 "H₂O

Absolute Pressure: (Pa) 24.9 "Hg

Pa = Pb + Ps/13.6

Nozzle Size (inch) 0.5

Impinger Train Weights (grams)

	#1	#2	#3	#4	SUM
Gross	679.3	645.6	496.5	869.1	2690.5
Tare	604.1	620.4	493.2	827.0	2544.7
Net Gain	75.2	25.2	3.3	42.1	145.8
Vws =	6.863	SCF			

Sample Point	Time	Pilot Tube		(Pm) H	Volume (ft ³)	Stack Temp. (Ts)	Oven Temp.	Last Impinger Temp.	Meter Temp (Tm)		Vacuum "Hg
		P	P						In	Out	
1	1122	-	-	0.96	777.78	140	238	53	64	63	5.0
2	1207	-	-	0.95	804.50	199	296	41	79	68	5.0
3	1252	-	-	0.96	831.60	228	315	41	82	72	5.0
4	1337	-	-	0.98	858.75	320	319	42	84	75	5.0
5	1422	-	-	0.98	886.09	313	320	42	86	76	5.0
6	1507	-	-	0.98	913.59	307	320	43	86	77	5.2
7	1552	-	-	1.03	941.26	311	326	41	87	78	5.5
8	1622	-	-	1.01	960.23	307	328	42	87	78	5.5
9	1652	-	-	0.98	978.52	302	328	44	38	78	5.0
10	1713	-	-	1.40	993.15	331	330	45	33	78	6.0

Total 368 0.00 0.00 Net 215.37 ft³

Average 368 0.00 0.00 2762.6 831 743

1.023 83 74

Pm, "Hg abs. = 24.98 Ts, °R = 736 Tm, °R = 539

Total SCF & ACF Sampled = 183.736 SCF 306.70 ACF

Total DSCF Samples = 176.873 DSCF

% Moisture = 3.74 %

Dust Concentration = 0.0008 gr./DSCF

Stack Gas Velocity, ft/sec = 0.00

Total Solid Sample Weight

Nomex Filter Gross, g	5.0477	0.0089
Nomex Filter Tare, g	5.0409	0.6135
Nomex Filter Net, g	0.0068	0.6114
		0.0021

4-INCH BATCH QUARTZ KILN
Thermal Treatment Data Sheet

Test # 3

Project # 8184
Date 10-26-93

Time	TEMPERATURES						GAS FLOWS				PRESSURES			COOLING WATER			GAS ANALYSIS			
	Kiln Control °C	Kiln °C	Kiln Outlet °C	A.B. Control °C	After-burner °C	Nomex inlet °C	Cooling H2O in °C	Cooling H2O out °C	N2 to Kiln scfm	Air to A.B. scfm	Gas to CEM scfm	Kiln Inlet "H2O	A.B. Inlet "H2O	Nomex Outlet "H2O	Flow Settings mm	Water Rates cc/min	Total Flowrate cc/min	CEM Readings		
																		O2 %	CO2 %	CO ppm
0900	-	23	227	950	932	63	-	-	0.1	0.5	0.03	2.1	1.0	0.8	-	-	-	16.0	0.0	6
0915	345	178	225	950	956	113	-	-	0.1	0.5	0.03	2.1	1.0	0.7	-	-	-	9.6	6.1	13
0930	340	300	250	965	967	129	-	-	0.1	0.5	0.03	2.1	1.0	0.7	-	-	-	12.0	3.9	35
0946	350	330	265	965	969	131	-	-	0.1	0.5	0.03	1.9	0.9	0.5	-	-	-	12.7	3.3	22
1002	365	341	278	970	973	131	-	-	0.1	0.5	0.03	2.0	1.0	0.8	-	-	-	11.0	4.8	15
1015	365	351	282	990	988	134	-	-	0.1	0.5	0.03	2.3	1.2	1.0	-	-	-	9.2	6.3	13
1032	370	353	310	990	987	135	-	-	0.1	0.5	0.03	3.2	2.1	1.0	-	-	-	10.3	5.7	18
1047	365	353	320	990	994	136	-	-	0.1	0.5	0.03	3.0	2.0	1.0	-	-	-	8.9	6.8	17
1115	360	351	325	990	995	136	-	-	0.1	0.5	0.03	3.0	2.0	0.9	-	-	-	10.5	5.4	16
1133	365	354	323	995	995	137	-	-	0.1	0.5	0.03	2.0	1.0	0.7	-	-	-	9.8	6.2	17
1145	365	355	322	995	996	137	-	-	0.1	0.5	0.03	1.9	0.9	0.5	-	-	-	10.8	5.3	19
1200	367	358	322	995	996	137	-	-	0.1	0.5	0.03	2.0	0.9	0.7	-	-	-	10.7	5.4	18
1215	375	362	319	995	996	136	-	-	0.1	0.5	0.03	2.2	1.0	0.6	-	-	-	10.9	5.0	19
1230	380	369	321	995	997	137	-	-	0.1	0.5	0.03	2.5	1.3	1.0	-	-	-	10.5	5.5	19
1245	390	381	321	995	997	138	-	-	0.1	0.5	0.03	3.1	2.0	1.8	-	-	-	9.9	6.1	17
1301	390	386	342	995	997	137	-	-	0.1	0.5	0.03	2.5	1.4	1.6	-	-	-	11.2	4.8	18
1317	410	394	352	995	997	136	-	-	0.1	0.5	0.03	2.5	1.4	0.9	-	-	-	13.0	3.1	16
1338	460	401	348	995	995	135	-	-	0.1	0.5	0.03	2.1	1.0	0.5	-	-	-	15.1	1.1	15
1402	590	555	360	995	996	134	-	-	0.1	0.5	0.03	2.1	1.0	0.8	-	-	-	15.7	0.4	15
1416	715	691	370	990	996	134	-	-	0.1	0.5	0.03	2.3	1.1	0.7	-	-	-	16.0	0.1	14
1436	720	703	384	995	996	133	-	-	0.1	0.5	0.03	2.4	1.2	0.9	-	-	-	16.1	0.0	12
1450	700	694	406	990	997	140	-	-	0.2*	0.5	0.03	3.8	1.0	0.4	-	-	-	18.5	1.4	19
1516	715	689	421	990	996	153	-	-	0.2*	0.5	0.03	4.0	1.4	0.7	-	-	-	19.5	0.3	18

* air, not N2

Starting Sample Weight, g 2600
Ending Sample Weight, g 20 (ash recovered)

Hazen Research, Inc.

4-INCH BATCH QUARTZ KILN
Thermal Treatment Data Sheet

Test # 2

Project # 8184
Date 10-22-93

Time	TEMPERATURES				GAS FLOWS				PRESSURES				COOLING WATER				GAS ANALYSIS			
	Kiln Control	Kiln	Kiln Outlet	A.B. Control	After-burner	Nonex inlet	Cooling H2O in	Cooling H2O out	N2 to Kiln	Air to A.B.	Gas to CEM	Kiln Inlet	A.B. Inlet	Nonex Outlet	Flow Settings	Water Rates	Total Flowrate	O2	CO2	CO
	°C	°C	°C	°C	°C	°C	°C	°C	scfm	scfm	scfm	°H2O	°H2O	°H2O	mm	cc/min	cc/min	%	%	ppm
1000	20	23	107	790	780	75	-	-	0.1	0.5	0.03	4.0	2.8	2.6	-	-	-	15.1	0.01	19
1015	330	190	145	880	880	101	-	-	0.1	0.5	0.03	2.0	1.0	0.5	-	-	-	11.9	3.5	15
1030	310	289	224	980	975	120	-	-	0.1	0.5	0.03	2.1	1.0	0.7	-	-	-	13.0	2.6	20
1045	350	324	263	990	987	124	-	-	0.1	0.5	0.03	2.1	1.0	0.7	-	-	-	12.3	3.2	9
1100	365	343	288	1000	994	126	-	-	0.1	0.5	0.03	1.9	0.9	0.4	-	-	-	10.5	4.9	11
1130	365	356	316	1000	998	129	-	-	0.1	0.5	0.03	3.0	2.0	1.4	-	-	-	7.4	7.5	12
1145	365	358	342	1000	991	129	-	-	0.1	0.5	0.03	3.2	2.1	1.2	-	-	-	6.3	8.6	16
1200	370	353	352	995	991	132	-	-	0.1	0.5	0.03	2.6	1.5	1.0	-	-	-	8.3	6.8	20
1218	365	355	363	995	991	127	-	-	0.1	0.5	0.03	2.0	0.8	0.4	-	-	-	8.4	6.7	19
1230	365	357	360	995	994	134	-	-	0.1	0.5	0.03	2.2	1.1	0.6	-	-	-	7.5	7.5	19
1245	365	352	364	995	993	141	-	-	0.1	0.5	0.03	2.4	1.4	0.8	-	-	-	10.6	4.8	16
1300	375	360	356	995	993	140	-	-	0.1	0.5	0.03	2.0	1.0	0.5	-	-	-	9.1	6.2	15
1315	380	364	374	995	992	140	-	-	0.1	0.5	0.03	2.5	1.5	1.0	-	-	-	7.7	5.5	15
1331	395	373	402	995	993	142	-	-	0.1	0.5	0.03	2.7	1.6	1.2	-	-	-	8.2	6.9	15
1345	390	377	413	995	992	140	-	-	0.1	0.5	0.03	2.5	1.3	0.8	-	-	-	11.6	4.0	13
1405	425	402	402	995	994	140	-	-	0.1	0.5	0.03	2.2	1.0	0.7	-	-	-	10.8	4.4	33
1415	455	433	385	995	991	136	-	-	0.1	0.5	0.03	2.1	1.0	0.6	-	-	-	12.8	2.6	15
1430	515	476	360	995	992	135	-	-	0.1	0.5	0.03	1.1	0.6	0.2	-	-	-	14.7	0.9	11
1447	610	572	342	995	992	135	-	-	0.1	0.5	0.03	2.1	1.0	0.5	-	-	-	15.3	0.2	8
1505	630	602	363	995	992	135	-	-	0.1	0.5	0.03	2.3	1.2	0.8	-	-	-	15.6	0.03	9
1515	600	600	367	995	993	133	-	-	0.1*	0.5	0.03	1.8	0.6	0.2	-	-	-	17.9	1.2	9
1530	630	601	392	995	993	147	-	-	0.1*	0.5	0.03	3.6	1.2	0.7	-	-	-	18.7	0.6	10

* gas flow is air

Starting Sample Weight, g 200.0
Ending Sample Weight, g 1.8 (ash recovered)

Hazen Research, Inc.

4-INCH BATCH QUARTZ KILN Thermal Treatment Data Sheet

Test # 1

Project # 8184
Date 10-21-93

Time	TEMPERATURES						GAS FLOWS				PRESSURES			COOLING WATER			GAS ANALYSIS				
	Kiln Control °C	Kiln °C	Kiln Outlet °C	A.B. Control °C	After-burner °C	Nomex inlet °C	Cooling H2O in °C	Cooling H2O out °C	N2 to Kiln scfm	Air to A.B. scfm	Gas to CEM scfm	Kiln Inlet "H2O	A.B. Inlet "H2O	Nomex Outlet "H2O	Flow Settings mm	Water Rates cc/min	Total Flowrate cc/min	CEM Readings			
																		O2 %	CO2 %	CO ppm	
1125	-	223	222	980	976	64	-	-	0.1	0.5	0.03	1.2	0.8	0.6	-	-	-	16.0	0.02	3	
1135	300	138	232	970	974	92	-	-	0.1	0.5	0.03	1.5	0.5	0.2	-	-	-	15.0	0.74	14	
1145	300	228	244	980	978	92	-	-	0.1	0.5	0.03	1.9	1.0	0.6	-	-	-	12.8	2.9	16	
1200	320	243	265	980	982	95	-	-	0.1	0.5	0.03	2.4	1.5	1.1	-	-	-	12.6	3.2	17	
1215	340	320	280	980	983	94	-	-	0.1	0.5	0.03	1.9	0.9	0.7	-	-	-	12.3	3.4	13	
1230	350	336	299	990	985	100	-	-	0.1	0.5	0.03	1.9	1.0	0.7	-	-	-	11.8	3.9	14	
1250	365	354	316	990	986	109	-	-	0.1	0.5	0.03	2.4	1.4	1.0	-	-	-	9.3	6.0	15	
1315	365	350	328	990	986	110	-	-	0.1	0.5	0.03	2.4	1.7	1.0	-	-	-	8.8	6.6	15	
1330	370	350	334	990	987	150	-	-	0.1	0.5	0.03	3.0	2.0	1.0	-	-	-	9.4	5.9	12	
1345	365	354	346	990	987	165	-	-	0.1	0.5	0.03	2.4	1.6	0.8	-	-	-	7.8	7.3	11	
1400	365	352	345	990	987	158	-	-	0.1	0.5	0.03	2.5	1.2	0.9	-	-	-	9.3	6.0	9	
1415	365	351	352	990	984	154	-	-	0.1	0.5	0.03	2.0	1.0	0.8	-	-	-	10.4	5.1	8	
1430	370	359	363	990	985	155	-	-	0.1	0.5	0.03	2.2	1.2	0.8	-	-	-	7.7	7.4	10	
1450	380	366	347	990	986	154	-	-	0.1	0.5	0.03	1.9	1.0	0.6	-	-	-	8.9	6.3	9	
1500	380	366	350	990	985	153	-	-	0.1	0.5	0.03	3.0	2.0	1.8	-	-	-	10.7	4.8	8	
1515	395	384	351	990	986	155	-	-	0.1	0.5	0.03	1.8	0.8	0.4	-	-	-	5.8	8.9	12	
1530	420	394	358	990	986	156	-	-	0.1	0.5	0.03	1.8	0.8	0.4	-	-	-	9.8	5.6	9	
1545	450	428	363	990	985	156	-	-	0.1	0.5	0.03	1.8	0.8	0.5	-	-	-	11.3	4.2	7	
1600	520	493	359	990	983	154	-	-	0.1	0.5	0.03	2.1	1.1	0.8	-	-	-	15.1	0.8	4	
1615	520	505	358	995	981	154	-	-	0.1	0.5	0.03	2.1	1.1	0.8	-	-	-	15.6	0.37	4	
1636	520	504	358	995	982	154	-	-	0.1	0.5	0.03	2.1	1.1	0.8	-	-	-	15.8	0.2	4	
1645	495	496	352	990	982	149	-	-	0.1	0.5	0.03	2.1	1.0	0.7	-	-	-	18.4	1.2	5	
1700	525	493	366	990	981	168	-	-	0.2	0.5	0.03	3.7	1.5	1.0	-	-	-	19.2	0.6	6	

* a.r., not N2

Starting Sample Weight, g 200.1
Ending Sample Weight, g 1.6

(ash recovered)

Hazen Research, Inc.

4-INCH BATCH QUARTZ KILN Thermal Treatment Data Sheet

Test # Shaked

Project # 819A
Date 10/22/93

Time	TEMPERATURES						GAS FLOWS				PRESSURES			COOLING WATER			GAS ANALYSIS			
	Kiln Control °C	Kiln °C	Kiln Outlet °C	A.B. Control °C	After burner °C	Nomex inlet °C	Cooling H2O in °C	Cooling H2O out °C	N2 to Kiln scfm	Air to A.B. scfm	Gas to CEM scfm	Kiln Inlet "H2O	A.B. Inlet "H2O	Nomex Outlet "H2O	Flow Settings mm	Water Rates cc/min	Total Flowrate cc/min	O2 %	CEM Readings	
																			%	CO2 %
1000	-	22	258	920	908	100	-	-	0.27	0.5	0.03	2.5	0.5	0.4	-	-	-	13.6	0.0	0.7
1010	230	76	278	960	953	115	-	-	0.27	0.5	0.03	3.0	1.3	0.7	-	-	-	13.5	0.1	3.2
1020	215	148	291	962	970	117	-	-	0.27	0.5	0.03	3.0	1.0	0.8	-	-	-	13.4	0.4	8.3
1030	250	177	276	966	970	120	-	-	0.27	0.5	0.03	3.0	1.0	0.8	-	-	-	13.2	0.6	7.7
1040	260	206	294	970	969	118	-	-	0.27	0.5	0.03	2.9	1.0	0.7	-	-	-	13.1	0.7	7.8
1050	260	230	293	975	970	112	-	-	0.27	0.5	0.03	3.0	1.0	0.8	-	-	-	13.1	0.6	12.7
1060	300	250	276	980	973	117	-	-	0.27	0.5	0.03	3.0	1.1	0.8	-	-	-	12.8	0.9	18.0
1110	310	277	294	980	975	117	-	-	0.27	0.5	0.03	3.0	1.0	0.8	-	-	-	12.2	1.5	17
1121	325	298	299	980	976	120	-	-	0.27	0.54	0.03	3.0	1.1	0.8	-	-	-	12.4	1.4	19
1132	330	309	300	980	977	124	-	-	0.27	0.5	0.03	3.4	1.5	1.2	-	-	-	12.5	1.4	39
1140	345	319	303	985	978	127	-	-	0.27	0.5	0.03	3.0	1.2	0.8	-	-	-	11.8	1.7	32
1150	340	323	310	985	980	135	-	-	0.27	0.5	0.03	-	-	-	-	-	-	-	-	-
1200	345	328	321	985	982	147	-	-	0.27	0.5	0.03	2.8	1.2	0.8	-	-	-	11.0	2.0	13
1210	355	321	327	985	981	143	-	-	0.27	0.5	0.03	3.0	1.3	1.0	-	-	-	11.6	2.3	10
1230	365	350	336	990	984	152	-	-	0.27	0.5	0.03	3.0	1.0	0.2	-	-	-	10.9	2.2	8.2
1250	370	358	341	990	985	153	-	-	0.27	0.9	0.03	2.5	1.3	1.0	-	-	-	8.7	5.0	25
1300	375	360	346	990	984	153	-	-	0.27	0.52	0.03	1.5	0.0	0.0	-	-	-	7.7	5.8	572
1315	370	361	355	990	988	156	-	-	0.27	0.5	0.03	2.0	0.0	0.0	-	-	-	7.7	5.5	16
1330	390	362	344	990	987	153	-	-	0.27	0.5	0.03	4.0	2.2	2.0	-	-	-	6.5	6.5	8
1350	410	362	337	990	985	150	-	-	0.27	0.5	0.03	2.5	0.5	0.2	-	-	-	6.4	6.0	7
1400	405	375	339	995	986	154	-	-	0.27	0.5	0.03	3.5	2.0	1.6	-	-	-	8.7	4.7	29
1440	405	384	345	995	983	153	-	-	0.27	0.5	0.03	3.5	1.8	1.4	-	-	-	8.8	4.8	5
1500	420	386	349	995	985	153	-	-	0.27	0.5	0.03	3.5	2.0	1.4	-	-	-	9.8	3.8	5
1530	530	485	375	990	978	150	-	-	0.27	0.5	0.03	3.3	1.6	1.3	-	-	-	13.6	0.4	3
1550	535	504	390	990	976	147	-	-	-	-	-	-	-	-	-	-	-	13.9	0.04	6

Starting Sample Weight, g 200.7
Ending Sample Weight, g

Table 3. Low Temperature Ashing – Test Run #3

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
345	711	379	998	131	18	1.5	16
346	711	378	997	131	18	1.5	16
347	717	400	998	133	18	1.4	16
348	697	403	997	134	18	1.6	16
349	688	404	996	137	18	1.7	17
350	695	406	996	138	18	1.6	19
351	693	407	997	140	18	1.5	19
352	693	408	997	142	19	1.4	20
353	692	409	996	143	19	1.3	20
354	691	408	995	145	19	1.2	19
355	692	410	996	146	19	1.1	20
356	692	410	996	147	19	1.0	20
357	696	411	996	148	19	1.0	20
358	686	412	996	149	19	0.9	20
359	683	411	996	149	19	0.9	19
360	679	414	997	150	19	0.8	19
361	683	415	996	150	19	0.8	19
362	683	415	996	151	19	0.7	19
363	685	416	997	151	19	0.7	18
364	685	417	996	152	19	0.7	18
365	686	419	997	152	19	0.6	18
366	690	419	996	152	19	0.6	18
367	688	419	996	152	19	0.5	18
368	691	421	997	153	19	0.5	18
369	689	420	996	153	19	0.5	18
370	690	421	996	154	19	0.4	18
371	689	422	996	154	19	0.4	19
372	690	422	996	153	20	0.3	19
373	690	423	996	154	20	0.3	19
374	689	423	997	154	20	0.2	19
375	692	424	997	154	20	0.2	19
376	689	423	997	154	20	0.2	19
377	691	425	997	155	20	0.1	19
378	690	425	997	153	20	0.0	19
379	682	404	997	143	20	0.0	19
380	623	397	990	134	19	0.0	12
381	577	392	983	126	15	1.7	7
382	544	387	976	119	17	3.7	8
383	517	384	968	113	18	1.6	5
384	495	380	959	108	19	0.7	4
385	476	375	951	103	19	0.3	3

Table 3. Low Temperature Ashing – Test Run #3

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Airburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
302	557	358	996	134	15	0.6	15
303	557	360	996	134	16	0.4	15
304	562	361	996	134	16	0.2	15
305	573	363	996	134	16	0.2	14
306	593	364	996	134	16	0.2	14
307	615	364	996	134	16	0.2	14
308	637	364	995	134	16	0.3	14
309	658	364	996	134	16	0.3	14
310	660	365	996	134	16	0.3	14
311	667	366	996	134	16	0.2	14
312	675	367	997	134	16	0.1	14
313	674	368	997	134	16	0.1	14
314	679	369	996	134	16	0.1	14
315	674	369	997	134	16	0.1	14
316	688	369	996	134	16	0.1	14
317	690	370	996	134	16	0.1	14
318	690	371	997	134	16	0.1	14
319	701	372	996	133	16	0.1	13
320	698	372	996	133	16	0.1	13
321	703	373	997	133	16	0.1	13
322	700	374	997	133	16	0.1	13
323	704	375	997	133	16	0.1	12
324	702	376	996	133	16	0.1	12
325	703	376	996	133	16	0.1	12
326	702	377	997	133	16	0.1	12
327	704	379	997	133	16	0.0	12
328	703	378	996	133	16	0.0	12
329	704	380	998	133	16	0.0	12
330	703	381	997	134	16	0.0	12
331	704	381	997	134	16	0.0	12
332	705	382	997	134	16	0.0	12
333	705	382	997	134	16	0.0	12
334	699	382	997	133	16	0.0	12
335	705	383	997	134	16	0.0	12
336	701	384	997	133	16	0.0	12
337	703	381	998	133	16	0.0	12
338	708	379	997	132	17	0.0	12
339	702	380	998	131	18	0.6	13
340	708	382	997	131	18	1.2	15
341	714	382	998	131	18	1.8	15
342	704	382	997	131	18	1.9	16
343	701	381	997	132	18	1.7	16
344	697	380	997	131	18	1.6	16

Table 3. Low Temperature Ashing – Test Run #3

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
259	394	350	997	136	13	3.2	16
260	393	351	997	136	13	3.4	16
261	393	350	996	136	13	3.2	16
262	394	350	996	136	13	2.9	16
263	396	350	997	135	13	2.9	16
264	400	349	997	135	13	3.0	15
265	400	348	996	135	13	3.4	15
266	399	349	997	135	13	3.6	14
267	393	344	941	135	13	3.4	15
268	391	346	975	135	13	2.8	15
269	403	347	979	135	14	2.2	14
270	414	345	983	134	13	2.5	13
271	419	345	986	134	12	4.3	12
272	420	345	988	135	11	5.2	11
273	418	345	990	135	11	4.8	11
274	413	346	991	135	12	4.0	11
275	410	347	993	135	13	2.9	13
276	412	346	992	135	14	2.2	14
277	409	347	994	135	14	1.9	15
278	396	347	994	135	15	1.7	14
279	405	348	993	135	15	1.2	15
280	417	348	994	134	15	1.0	15
281	425	348	995	134	15	1.5	15
282	427	348	995	134	14	1.9	14
283	428	348	995	134	14	1.8	14
284	432	348	995	134	15	1.5	14
285	426	349	995	134	15	1.4	14
286	424	349	994	134	15	1.3	14
287	438	350	996	134	15	1.0	15
288	446	349	995	133	15	1.1	15
289	449	349	996	133	15	1.5	14
290	450	351	995	133	15	1.4	14
291	453	351	996	133	15	1.1	14
292	455	351	996	133	15	0.9	14
293	453	352	995	133	15	0.9	14
294	455	352	996	133	16	0.7	14
295	470	352	996	133	16	0.5	14
296	485	353	996	133	16	0.5	14
297	489	353	996	133	15	0.8	14
298	501	354	996	134	15	0.7	15
299	519	355	996	134	15	0.6	15
300	535	356	996	133	15	0.7	15
301	552	357	996	134	15	0.7	15

Table 3. Low Temperature Ashing – Test Run #3

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Airburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
216	373	321	997	137	11	5.0	19
217	373	320	996	137	11	4.9	19
218	374	322	997	137	11	5.3	19
219	373	321	998	136	11	5.3	18
220	372	319	997	136	11	4.9	18
221	374	318	997	137	12	4.4	18
222	374	318	997	136	12	4.3	19
223	375	318	997	136	11	4.7	18
224	375	318	997	136	11	4.7	18
225	378	319	997	136	11	4.5	18
226	381	320	997	136	11	5.0	18
227	381	321	997	137	10	6.0	17
228	381	321	997	138	9	6.4	17
229	380	322	997	138	10	6.2	17
230	379	322	997	137	10	5.7	17
231	381	323	997	137	11	5.0	17
232	383	324	997	137	11	4.9	17
233	383	325	998	136	11	5.4	17
234	382	326	998	137	10	5.6	17
235	384	328	997	137	11	5.2	17
236	386	330	997	137	11	5.2	18
237	386	333	998	137	10	5.7	17
238	385	335	997	137	10	5.8	17
239	385	337	997	137	11	5.3	17
240	386	339	997	137	11	4.7	18
241	386	340	997	137	11	4.6	18
242	386	342	997	137	11	4.8	18
243	385	343	997	137	11	4.7	18
244	385	349	997	137	12	4.2	18
245	389	348	997	136	12	3.8	17
246	392	344	997	136	12	4.2	16
247	391	344	998	136	11	5.1	16
248	390	350	995	136	11	5.2	17
249	389	352	997	136	11	4.7	17
250	389	353	998	136	12	4.1	16
251	390	353	998	136	13	3.6	17
252	394	352	997	136	13	3.5	16
253	397	351	998	136	12	4.0	16
254	396	352	997	136	12	4.5	15
255	395	351	997	136	12	4.4	15
256	391	351	997	136	12	4.0	16
257	391	352	998	136	13	3.5	16
258	393	351	998	136	13	3.1	16

Table 3. Low Temperature Ashing – Test Run #3

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
173	358	322	996	137	10	5.8	20
174	357	321	995	137	10	5.6	20
175	357	321	996	136	11	5.3	21
176	358	321	997	137	11	5.1	19
177	359	322	996	136	11	5.4	18
178	359	321	995	136	10	5.7	18
179	358	321	996	136	11	5.5	18
180	358	321	996	137	11	5.1	18
181	359	321	996	136	11	4.8	18
182	358	320	996	136	11	5.0	18
183	359	320	996	136	11	5.3	17
184	360	320	996	137	11	5.2	17
185	361	321	996	137	11	5.1	17
186	362	321	996	137	10	5.5	18
187	362	322	997	137	10	5.8	18
188	361	321	996	136	10	5.8	18
189	360	320	996	136	11	5.5	18
190	362	321	997	136	11	5.1	18
191	362	320	996	136	11	5.2	18
192	362	321	996	136	10	5.6	18
193	362	321	996	136	10	5.5	18
194	361	320	997	136	11	5.2	18
195	361	318	996	136	11	4.8	19
196	363	319	997	136	11	4.8	19
197	363	319	997	136	11	5.1	19
198	362	319	996	136	11	5.2	19
199	362	319	997	136	11	4.9	19
200	361	317	997	136	12	4.5	19
201	363	317	996	136	12	4.3	19
202	365	318	996	136	11	4.6	19
203	367	319	996	136	11	5.0	19
204	367	320	996	137	10	5.6	19
205	367	320	997	137	10	5.7	19
206	368	320	997	137	10	5.6	19
207	370	321	997	137	10	5.9	19
208	369	320	997	137	9	6.5	18
209	370	322	997	137	9	6.5	18
210	370	321	998	137	10	6.1	18
211	372	321	998	137	11	5.5	19
212	372	321	997	136	10	5.5	19
213	372	322	997	137	10	5.9	19
214	371	321	996	137	10	5.9	19
215	371	321	998	137	10	5.6	19

Table 3. Low Temperature Ashing – Test Run #3

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Klin Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
130	355	325	997	137	7	8.9	17
131	355	325	997	137	7	8.1	17
132	354	326	997	137	8	7.6	17
133	352	325	996	137	9	6.8	17
134	351	325	996	137	10	6.3	17
135	351	325	996	136	10	5.6	17
136	351	324	995	136	10	5.4	17
137	351	324	996	136	10	5.7	17
138	352	324	994	135	10	5.9	17
139	352	324	995	136	10	5.8	16
140	352	323	994	136	10	5.9	17
141	353	324	995	136	10	6.3	16
142	352	324	994	136	10	6.3	16
143	352	324	995	136	10	6.2	16
144	352	324	994	136	10	5.9	16
145	351	323	995	136	11	5.4	16
146	352	322	994	136	11	5.0	16
147	351	322	994	136	11	5.1	16
148	351	321	995	136	11	5.3	16
149	352	321	995	136	11	5.3	17
150	351	321	995	136	11	5.1	17
151	352	321	995	136	11	4.8	16
152	353	322	995	136	11	5.3	16
153	354	322	995	136	10	5.9	17
154	355	322	995	136	10	6.2	17
155	355	322	995	137	10	6.1	17
156	354	321	995	137	10	5.8	18
157	354	322	995	137	11	5.5	18
158	356	322	995	137	11	5.4	18
159	357	321	995	137	9	6.3	18
160	358	322	996	137	8	7.2	19
161	359	323	996	137	8	7.6	19
162	357	322	996	137	8	7.4	19
163	357	322	995	138	9	7.0	19
164	356	323	997	138	10	6.4	19
165	355	322	997	137	10	5.8	19
166	355	322	996	137	11	5.2	20
167	356	322	996	137	11	5.3	19
168	356	322	996	137	11	5.5	20
169	356	322	996	137	11	5.4	20
170	357	322	996	137	11	5.2	20
171	357	322	996	136	11	5.2	20
172	358	322	996	137	10	5.6	20

Table 3. Low Temperature Ashing – Test Run #3

Time (min)	Temperature				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
87	353	307	992	136	10	6.1	14
88	354	307	991	136	10	5.9	14
89	354	308	991	136	10	6.0	15
90	356	310	992	135	10	6.2	15
91	355	311	992	136	10	6.2	14
92	354	310	986	136	9	6.3	15
93	354	311	989	136	10	6.1	15
94	357	312	990	136	10	5.9	22
95	358	313	990	136	8	7.3	19
96	358	314	991	136	8	7.7	18
97	358	315	991	136	8	8.0	18
98	357	316	992	136	8	8.0	17
99	356	317	993	136	8	7.6	18
100	355	318	993	137	8	7.4	18
101	354	318	994	136	9	6.7	17
102	354	318	993	136	9	6.8	17
103	355	319	994	136	9	7.0	18
104	353	319	994	136	9	7.0	17
105	353	320	993	137	9	6.9	17
106	353	319	994	136	9	6.6	17
107	352	319	994	136	9	6.3	17
108	353	320	994	136	9	6.7	17
109	353	321	994	136	9	6.7	16
110	352	321	994	136	9	6.9	17
111	351	321	994	136	9	6.7	17
112	353	322	993	136	10	6.3	17
113	352	322	994	135	9	6.5	17
114	352	321	994	135	9	6.7	16
115	352	321	994	135	9	6.8	17
116	353	322	995	135	9	6.5	17
117	355	320	994	135	9	6.6	17
118	357	321	995	135	8	7.6	17
119	358	320	996	135	4	10.5	17
120	359	322	997	136	1	13.2	453
121	357	324	997	137	3	12.8	506
122	354	324	997	137	6	9.4	60
123	353	323	996	136	9	7.3	23
124	354	323	996	135	9	7.0	19
125	354	323	997	135	7	8.0	18
126	355	323	996	135	7	8.8	17
127	356	323	997	135	6	9.4	17
128	356	324	997	136	6	9.6	17
129	356	325	997	137	6	9.3	17

Table 3. Low Temperature Ashing – Test Run #3

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
44	328	264	968	131	13	3.2	25
45	329	264	969	131	13	3.3	23
46	329	265	970	131	13	3.3	22
47	330	266	969	131	13	3.3	22
48	330	267	970	131	13	3.3	20
49	331	268	970	131	12	3.5	19
50	332	269	970	131	12	3.5	19
51	333	270	970	131	12	3.6	18
52	335	271	971	131	12	3.9	17
53	336	272	971	131	12	4.2	17
54	336	273	972	131	12	4.2	17
55	336	274	972	131	12	4.2	17
56	336	274	972	131	12	4.0	18
57	337	275	972	131	12	3.8	18
58	338	276	972	131	12	3.9	17
59	338	276	973	131	12	4.0	16
60	339	277	973	131	12	4.0	18
61	340	277	973	131	12	4.0	17
62	341	278	973	131	12	4.4	16
63	341	278	973	131	11	4.7	16
64	343	279	974	132	11	4.9	16
65	344	279	977	132	11	4.8	16
66	344	278	976	132	10	5.5	15
67	346	277	977	133	10	6.1	15
68	346	278	979	133	9	6.3	16
69	346	277	980	134	10	6.3	15
70	347	280	983	134	10	6.1	15
71	347	284	984	134	10	5.8	14
72	347	283	985	134	10	5.5	14
73	350	279	986	134	10	5.8	14
74	349	279	987	134	9	6.3	14
75	350	282	987	134	9	6.5	14
76	352	282	988	134	10	6.2	14
77	353	285	989	134	9	6.8	15
78	353	288	989	134	9	7.1	14
79	352	291	989	134	9	6.8	15
80	352	293	989	135	9	6.7	15
81	353	295	990	135	9	6.4	15
82	352	298	990	134	10	5.9	14
83	352	299	990	135	10	6.1	15
84	353	301	991	135	10	6.2	14
85	354	304	991	135	10	6.1	14
86	353	305	991	135	10	6.3	14

Table 3. Low Temperature Ashing – Test Run #3

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
1	23	227	929	57	16	-0.0	6
2	24	228	933	63	16	-0.1	7
3	25	229	936	68	16	-0.0	8
4	27	231	938	73	16	-0.1	9
5	32	232	940	78	16	-0.1	10
6	40	233	942	82	16	-0.1	14
7	50	234	945	87	16	-0.0	89
8	60	234	946	90	16	-0.0	52
9	71	234	948	94	16	-0.0	38
10	84	233	950	97	16	0.1	34
11	100	231	951	100	16	0.4	27
12	117	228	952	103	15	0.9	28
13	136	225	953	106	14	2.1	29
14	156	224	955	109	12	4.0	19
15	173	225	956	112	10	5.4	15
16	189	226	957	114	10	6.0	14
17	203	228	959	116	9	6.2	13
18	216	230	960	118	9	6.3	13
19	228	232	961	120	9	6.2	13
20	238	234	962	122	10	6.0	14
21	247	235	963	122	10	5.7	15
22	254	237	963	123	10	5.4	16
23	262	239	964	124	11	5.0	18
24	269	240	964	125	11	4.9	19
25	275	242	965	126	11	5.0	20
26	280	244	965	127	11	4.9	20
27	285	245	965	128	11	4.6	23
28	290	247	966	128	12	4.3	26
29	295	248	966	128	12	4.2	29
30	298	249	966	129	12	4.2	30
31	302	251	966	129	12	4.1	31
32	305	252	967	129	12	3.9	35
33	307	254	967	130	12	3.6	38
34	310	255	966	130	13	3.4	41
35	313	255	967	130	13	3.3	37
36	316	256	966	130	12	3.7	30
37	319	257	967	130	12	4.1	25
38	322	258	968	130	12	4.4	23
39	323	259	968	131	12	4.3	23
40	324	261	968	131	12	4.1	24
41	324	261	969	131	12	3.8	26
42	326	262	969	131	12	3.5	27
43	327	263	969	131	13	3.3	27

Table 2. Low Temperature Ashing Test – Test Run #2

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
302	596	361	993	136	16	0.0	8
303	604	363	993	136	16	0.0	9
304	596	363	993	136	16	0.0	9
305	605	365	993	135	16	0.0	9
306	599	364	993	135	16	0.0	9
307	597	360	992	132	16	0.0	9
308	614	362	994	134	16	0.4	9
309	607	364	993	135	17	1.8	10
310	610	365	994	134	17	2.1	10
311	605	365	993	134	17	1.8	10
312	601	365	993	133	18	1.6	10
313	598	366	993	133	18	1.4	10
314	598	366	993	133	18	1.3	9
315	600	367	994	132	18	1.2	9
316	596	367	994	131	18	1.2	9
317	592	367	993	131	18	1.1	9
318	593	367	994	132	18	1.1	9
319	589	367	993	133	18	1.0	9
320	590	368	994	134	18	1.0	9
321	591	372	993	135	18	0.9	9
322	588	379	994	137	18	1.0	9
323	589	383	993	139	18	1.1	9
324	589	384	994	141	18	1.0	10
325	585	385	994	142	18	0.9	10
326	586	386	994	143	18	0.9	10
327	591	387	993	145	19	0.8	10
328	599	390	994	146	19	0.8	10
329	602	391	994	146	19	0.7	10
330	602	392	993	147	19	0.7	10
331	605	393	994	147	19	0.7	10
332	602	393	994	148	19	0.6	10
333	606	393	993	149	19	0.6	10
334	604	394	994	150	19	0.5	10
335	606	394	993	151	19	0.5	10
336	604	395	994	151	19	0.4	11
337	604	394	993	152	19	0.4	11
338	607	396	994	153	19	0.3	11
339	605	396	994	153	19	0.3	11
340	607	396	994	153	19	0.2	12
341	605	396	993	153	19	0.2	12
342	606	396	994	153	19	0.1	13
343	607	390	986	156	19	0.0	14

Table 2. Low Temperature Ashing Test – Test Run #2

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
259	434	382	993	136	11	3.3	15
260	432	379	992	131	11	4.3	14
261	436	378	992	133	13	2.8	19
262	440	376	992	134	13	2.3	12
263	445	374	992	135	13	2.2	11
264	447	371	992	136	13	2.2	11
265	455	370	992	136	14	1.8	11
266	460	367	992	135	14	1.8	11
267	465	365	991	136	14	1.7	11
268	470	364	991	136	14	1.5	11
269	470	361	991	136	14	1.2	11
270	475	360	992	136	15	0.9	11
271	484	358	991	134	15	0.8	11
272	490	356	991	135	15	0.8	11
273	499	355	992	134	15	0.8	11
274	506	354	992	134	15	0.8	10
275	505	352	991	134	15	0.7	10
276	510	350	991	134	15	0.6	10
277	516	349	991	135	15	0.5	10
278	529	348	990	134	15	0.5	10
279	536	346	991	134	15	0.5	10
280	536	346	992	134	15	0.5	9
281	546	344	991	134	15	0.4	9
282	558	343	991	134	15	0.4	9
283	559	343	992	135	15	0.4	9
284	555	342	991	135	15	0.4	9
285	566	342	993	135	15	0.3	9
286	575	341	991	135	15	0.3	9
287	572	341	991	135	15	0.3	8
288	583	343	991	135	15	0.2	8
289	582	345	991	135	15	0.2	8
290	588	346	992	136	15	0.2	8
291	589	349	993	136	15	0.2	8
292	591	350	992	136	15	0.2	8
293	599	352	993	136	15	0.1	8
294	594	353	992	136	15	0.1	8
295	601	355	992	136	15	0.1	8
296	597	356	992	136	15	0.1	8
297	601	357	992	136	16	0.1	8
298	603	358	992	135	16	0.1	8
299	589	359	992	135	16	0.1	8
300	604	361	993	135	16	0.1	8
301	602	361	992	135	16	0.1	8

Table 2. Low Temperature Ashing Test – Test Run #2

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
216	377	409	992	144	8	6.9	15
217	376	408	993	146	8	6.9	15
218	376	407	992	144	9	6.4	14
219	378	405	992	141	10	5.8	14
220	378	405	992	140	10	5.1	14
221	378	405	993	139	10	5.1	14
222	377	409	992	140	10	5.4	14
223	376	413	992	140	10	5.4	14
224	375	414	992	140	11	5.0	14
225	378	414	993	140	11	4.4	14
226	378	412	992	138	12	4.0	13
227	377	413	992	134	12	3.8	13
228	381	409	991	124	11	4.0	13
229	385	413	993	144	10	4.3	13
230	385	407	992	134	8	4.9	13
231	385	409	993	134	9	4.7	2,324
232	383	409	993	135	10	4.3	2,599
233	382	409	993	135	10	4.9	2,079
234	384	409	992	136	10	4.8	688
235	387	408	993	137	11	4.4	222
236	394	405	993	136	11	4.0	102
237	399	394	993	137	11	3.9	62
238	408	398	993	139	10	4.3	45
239	411	403	995	138	9	5.5	38
240	409	404	995	127	6	7.2	36
241	407	404	995	127	3	9.6	35
242	395	402	994	137	2	11.8	59
243	393	404	994	140	5	10.2	360
244	396	405	994	139	7	8.2	240
245	400	404	994	139	10	6.3	97
246	401	403	994	139	11	4.9	49
247	403	402	993	139	11	4.4	32
248	402	401	993	140	11	4.3	25
249	401	400	992	140	11	4.1	21
250	399	399	992	139	12	3.8	20
251	399	397	990	139	12	3.5	18
252	405	395	991	139	13	3.0	18
253	408	394	991	139	13	2.6	18
254	410	391	991	138	13	2.3	17
255	415	390	991	138	13	2.3	16
256	426	387	991	137	13	2.5	16
257	434	384	992	136	13	2.6	16
258	435	384	992	137	12	2.7	15

Table 2. Low Temperature Ashing Test – Test Run #2

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
173	358	367	993	138	10	5.5	16
174	357	368	993	138	9	5.8	16
175	358	368	993	139	10	5.6	16
176	359	361	993	139	10	5.4	16
177	359	358	993	138	10	5.6	16
178	360	356	993	139	9	6.3	16
179	360	361	995	140	9	6.3	16
180	361	357	992	140	9	6.0	16
181	362	356	992	140	9	6.0	16
182	362	358	992	141	8	6.8	16
183	361	358	992	141	8	6.8	16
184	362	359	992	141	9	6.5	16
185	364	363	993	141	9	6.2	15
186	364	367	993	141	8	6.8	16
187	363	369	993	141	8	7.0	16
188	362	369	992	141	8	6.9	16
189	363	371	992	142	9	6.4	16
190	365	373	993	141	9	5.9	15
191	365	375	992	141	9	6.1	15
192	363	377	992	142	9	6.5	15
193	362	377	992	141	9	6.3	15
194	364	376	992	141	9	6.0	15
195	364	375	992	141	10	5.5	15
196	366	377	992	140	10	5.4	14
197	364	378	992	142	9	5.7	15
198	363	382	992	141	9	5.8	15
199	363	388	992	141	10	5.5	15
200	366	389	992	140	11	4.9	14
201	365	389	991	140	11	4.7	14
202	368	391	992	140	10	5.1	14
203	373	379	993	140	10	5.2	14
204	374	381	993	141	9	5.5	14
205	374	387	993	142	7	7.4	15
206	373	391	993	142	7	8.0	15
207	372	394	993	142	7	7.9	15
208	372	395	993	143	8	7.4	15
209	375	398	993	141	8	6.8	15
210	375	401	993	141	9	6.4	15
211	374	403	993	141	8	6.8	15
212	374	402	993	142	8	6.9	15
213	377	404	992	143	9	6.5	15
214	378	406	993	143	9	6.0	15
215	378	408	993	143	9	6.3	15

Table 2. Low Temperature Ashing Test – Test Run #2

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
130	354	360	992	134	8	7.2	19
131	353	360	992	134	8	7.1	19
132	355	359	992	132	8	6.8	20
133	354	360	991	132	8	6.7	19
134	355	361	992	131	8	6.8	19
135	354	361	991	130	8	7.2	20
136	353	362	991	128	8	7.0	19
137	354	364	992	128	8	6.9	19
138	355	364	991	128	9	6.4	19
139	355	365	992	127	8	6.6	19
140	355	365	992	127	8	6.8	19
141	353	364	991	127	8	6.8	18
142	353	365	992	127	8	6.7	19
143	354	366	991	128	9	6.4	19
144	354	364	992	129	9	6.4	25
145	355	362	992	130	9	6.5	24
146	357	360	992	131	9	6.4	22
147	358	360	993	131	9	6.4	21
148	358	362	992	131	8	7.1	20
149	357	362	992	133	7	7.8	20
150	357	362	993	134	7	7.8	19
151	356	360	993	135	8	7.5	19
152	354	357	992	135	8	7.1	19
153	355	356	993	137	8	6.7	19
154	356	355	992	137	9	6.3	19
155	358	355	992	137	9	6.3	18
156	357	357	992	138	8	6.7	18
157	356	357	992	138	8	7.0	18
158	355	357	992	139	8	6.9	18
159	353	359	992	139	9	6.4	18
160	353	358	992	140	9	6.3	18
161	354	359	991	140	10	5.8	17
162	354	359	992	140	9	5.8	18
163	354	359	992	139	9	5.8	17
164	353	358	993	140	10	5.7	17
165	352	362	992	140	10	5.5	17
166	353	363	992	140	10	5.0	17
167	354	362	991	140	11	4.8	16
168	354	363	993	140	10	5.3	17
169	353	367	993	141	10	5.3	17
170	353	368	992	140	11	5.0	16
171	356	368	993	138	11	4.6	16
172	357	367	993	137	10	4.8	16

Table 2. Low Temperature Ashing Test – Test Run #2

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
87	354	315	998	127	8	7.2	12
88	353	316	998	127	9	6.6	12
89	354	317	999	128	9	6.3	12
90	356	315	998	128	8	6.6	12
91	356	318	998	128	8	7.2	12
92	356	320	998	128	8	6.9	12
93	355	321	996	129	9	6.8	12
94	357	321	996	130	8	6.7	13
95	359	322	995	129	8	6.6	12
96	360	326	994	128	7	7.8	13
97	359	329	994	129	7	7.9	14
98	358	331	994	130	7	8.3	13
99	357	332	993	131	8	7.7	12
100	356	334	993	129	8	7.2	12
101	358	335	993	129	8	7.2	102
102	358	337	993	130	7	7.8	507
103	358	338	992	130	7	7.8	162
104	356	339	992	131	7	8.1	26
105	359	341	993	129	7	7.4	14
106	359	342	992	129	7	7.9	13
107	358	343	992	130	7	8.3	15
108	357	346	992	130	7	7.8	19
109	356	345	992	132	8	7.6	24
110	357	346	992	131	8	7.0	23
111	357	346	991	131	8	7.1	22
112	357	347	991	130	7	7.4	21
113	357	349	992	132	7	7.7	21
114	355	350	991	132	8	7.1	21
115	354	349	991	132	8	6.9	21
116	357	350	991	132	8	6.8	20
117	357	351	991	132	8	7.1	20
118	356	352	992	133	8	7.4	20
119	355	353	991	132	8	7.1	20
120	354	351	991	132	8	7.3	20
121	357	353	991	132	8	6.7	20
122	358	354	991	132	8	7.3	20
123	356	354	992	132	7	7.7	20
124	356	354	992	132	7	7.8	20
125	354	354	991	132	8	7.5	20
126	354	357	992	133	8	7.3	20
127	355	357	992	134	8	6.8	20
128	356	357	992	133	8	6.9	20
129	355	359	991	133	8	7.2	20

Table 2. Low Temperature Ashing Test – Test Run #2

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
44	319	261	986	124	13	2.6	10
45	323	263	987	124	13	2.8	10
46	326	265	987	124	13	3.0	10
47	328	267	988	124	12	3.5	10
48	329	269	989	124	12	3.9	9
49	330	271	989	125	11	4.0	9
50	332	273	990	125	11	4.1	10
51	333	275	991	125	11	4.2	10
52	333	277	992	126	11	4.3	10
53	334	278	992	126	11	4.1	10
54	336	280	993	126	11	4.1	10
55	336	282	993	126	11	4.2	11
56	336	283	992	126	11	4.4	11
57	337	285	993	127	11	4.4	11
58	339	287	994	127	11	4.2	11
59	342	288	993	127	11	4.1	11
60	343	289	994	126	11	4.4	11
61	344	291	994	126	10	4.9	11
62	344	292	995	126	10	5.0	11
63	344	294	995	126	11	4.9	10
64	346	295	995	126	11	4.8	10
65	348	297	996	126	10	5.0	10
66	347	298	995	127	10	5.3	11
67	346	299	996	128	10	5.2	11
68	346	301	996	128	10	5.0	11
69	348	302	996	128	11	4.9	11
70	348	304	996	129	11	4.7	11
71	348	304	997	129	11	4.8	11
72	347	306	997	130	11	4.8	11
73	349	306	996	129	11	4.6	11
74	351	307	996	129	11	4.3	11
75	352	308	997	128	10	4.9	11
76	353	309	997	129	10	5.5	11
77	352	309	997	128	10	5.6	11
78	351	310	997	129	10	5.6	12
79	349	312	997	128	10	5.2	11
80	351	312	997	129	10	5.1	11
81	352	313	997	128	10	5.2	11
82	353	315	997	129	10	5.4	11
83	352	314	998	128	10	5.4	11
84	353	312	998	129	10	5.4	11
85	354	314	998	128	9	5.9	11
86	355	312	998	128	9	6.1	12

Table 2. Low Temperature Ashing Test – Test Run #2

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Aft. burner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
1	22	105	718	68	16	0.0	14
2	23	107	727	74	16	0.0	15
3	25	109	762	75	16	0.0	21
4	30	111	688	78	16	0.0	25
5	37	113	594	81	16	0.0	30
6	46	115	610	83	16	0.0	47
7	57	118	623	86	16	0.0	70
8	71	121	620	88	16	0.0	50
9	87	123	323	90	16	0.1	15
10	106	125	55	92	15	0.2	7
11	126	127	240	93	15	0.5	6
12	147	131	791	95	14	1.1	6
13	165	136	869	98	13	2.1	8
14	181	141	884	99	13	2.9	13
15	194	146	894	101	12	3.4	15
16	206	151	902	103	12	3.8	16
17	217	156	910	105	11	4.1	15
18	226	163	919	107	11	4.2	15
19	234	169	927	108	11	4.2	15
20	242	176	935	110	11	4.2	16
21	249	182	941	111	11	4.0	17
22	256	187	949	113	12	3.8	18
23	263	193	955	114	12	3.8	19
24	268	198	958	115	12	3.9	18
25	272	202	962	115	12	3.9	19
26	276	207	966	116	12	3.7	19
27	279	211	969	117	12	3.5	21
28	281	215	971	118	12	3.2	22
29	285	219	973	119	13	2.9	22
30	288	222	975	120	13	2.7	22
31	291	226	976	121	13	2.6	20
32	293	229	978	121	13	2.6	19
33	294	232	978	121	13	2.5	18
34	296	235	979	121	13	2.3	17
35	299	238	980	122	13	2.2	15
36	302	241	981	122	14	2.1	14
37	303	243	982	122	14	2.1	13
38	305	246	983	123	14	2.1	13
39	308	249	984	123	14	2.0	12
40	310	251	983	123	14	2.1	11
41	312	253	984	124	13	2.2	11
42	315	256	985	124	13	2.3	10
43	317	258	986	124	13	2.4	10

Table 1. Low Temperature Ashing Test – Test Run #1

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
337	493	366	981	168	19	0.63	6
338	495	367	982	169	19	0.57	6
339	496	368	981	169	19	0.53	6
340	495	369	982	170	19	0.48	6
341	496	369	981	171	19	0.42	6
342	496	370	981	171	19	0.37	6
343	495	370	981	172	19	0.32	6
344	496	371	981	172	20	0.27	6
345	497	371	980	173	20	0.24	7
346	496	371	981	173	20	0.20	6
347	497	372	981	174	20	0.16	7
348	498	373	981	174	20	0.13	7
349	496	373	981	174	20	0.10	7
350	483	363	974	148	20	0.08	7

Table 1. Low Temperature Ashing Test – Test Run #1

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
289	504	359	982	153	16	0.46	4
290	504	358	982	153	16	0.43	3
291	502	359	981	153	16	0.42	4
292	504	359	982	154	16	0.41	4
293	505	358	981	154	16	0.37	4
294	502	358	981	154	16	0.36	4
295	504	358	981	153	16	0.34	4
296	505	358	981	153	16	0.33	4
297	503	358	981	153	16	0.33	4
298	503	358	981	153	16	0.31	4
299	506	359	981	153	16	0.29	4
300	504	358	982	153	16	0.28	4
301	503	359	981	153	16	0.28	4
302	505	357	982	153	16	0.26	4
303	505	359	982	153	16	0.25	4
304	502	359	982	153	16	0.25	4
305	504	358	982	153	16	0.24	4
306	507	359	982	153	16	0.22	4
307	504	359	981	153	16	0.21	4
308	503	352	983	151	16	0.20	4
309	510	355	981	148	17	0.18	4
310	506	353	982	147	18	0.19	5
311	504	354	983	146	18	0.61	4
312	502	352	983	144	18	1.02	4
313	502	352	983	143	18	1.07	4
314	502	351	983	143	18	1.14	4
315	501	351	982	143	18	1.26	4
316	500	351	982	144	18	1.35	4
317	499	351	983	144	18	1.41	5
318	498	351	982	145	18	1.39	5
319	497	352	982	146	18	1.46	5
320	496	352	982	147	18	1.38	5
321	495	351	983	148	18	1.32	5
322	497	352	982	148	18	1.26	4
323	496	352	982	149	18	1.23	5
324	494	351	982	150	18	1.17	4
325	492	351	982	150	18	1.12	5
326	497	351	982	150	19	1.09	5
327	499	351	982	150	18	1.14	5
328	497	354	982	152	19	1.12	5
329	489	358	982	156	19	1.13	5
330	483	360	982	158	19	1.12	5
331	480	360	981	161	19	1.05	5
332	483	362	981	162	19	0.99	6
333	490	363	981	164	19	0.94	6
334	492	365	982	165	19	0.88	6
335	494	365	981	167	19	0.77	6
336	494	366	981	167	19	0.69	6

Table 1. Low Temperature Ashing Test – Test Run #1

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Airburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
241	392	359	987	156	7	7.88	11
242	392	361	987	156	6	8.47	12
243	390	359	987	156	7	7.80	11
244	391	360	987	155	9	6.77	10
245	394	359	986	156	10	5.86	9
246	395	360	987	155	9	6.29	10
247	394	360	986	156	8	6.74	10
248	395	359	986	156	9	6.19	10
249	399	357	986	156	10	5.42	9
250	402	357	987	156	9	5.71	9
251	403	358	986	156	8	6.85	10
252	406	358	986	156	9	6.67	10
253	407	359	986	156	8	6.73	10
254	408	358	986	156	8	7.20	11
255	409	358	986	156	9	6.65	10
256	414	357	987	156	9	6.09	9
257	417	358	986	156	9	6.31	9
258	417	358	986	156	9	6.80	10
259	416	360	986	156	10	6.01	10
260	421	362	985	156	11	4.98	9
261	424	363	986	156	11	4.44	8
262	427	364	986	155	11	4.83	8
263	430	364	986	156	11	4.44	8
264	431	364	986	155	12	4.13	7
265	436	363	985	155	12	3.65	7
266	445	364	985	155	12	3.24	7
267	452	363	984	155	12	3.51	7
268	454	363	985	155	12	3.68	7
269	458	362	984	155	13	2.87	7
270	464	363	984	155	14	2.13	6
271	477	363	984	154	14	1.84	6
272	481	363	984	154	14	1.97	7
273	481	362	984	154	14	1.91	7
274	484	362	983	154	15	1.34	6
275	492	361	983	154	15	1.05	5
276	493	361	984	154	15	1.06	5
277	491	361	983	154	15	0.97	5
278	495	361	983	154	15	0.84	5
279	496	360	983	154	15	0.77	4
280	500	360	982	154	15	0.73	4
281	501	360	983	154	15	0.70	4
282	500	359	982	154	15	0.66	4
283	503	359	982	154	15	0.61	4
284	503	359	981	153	15	0.61	4
285	500	359	981	154	15	0.58	4
286	503	359	981	153	15	0.53	4
287	504	359	982	154	15	0.52	4
288	502	358	982	153	15	0.50	4

Table 1. Low Temperature Ashing Test – Test Run #1

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
193	360	352	986	155	9	6.74	9
194	361	350	986	155	8	6.71	9
195	361	351	987	155	8	6.91	9
196	360	355	986	154	8	6.99	9
197	359	354	986	154	9	6.60	9
198	359	352	986	154	10	5.96	9
199	361	351	986	155	10	5.51	8
200	361	349	986	155	10	5.72	8
201	361	349	986	155	9	6.14	9
202	362	349	986	155	9	5.98	9
203	364	349	986	156	9	6.07	9
204	365	349	986	155	8	6.86	10
205	364	348	986	155	8	7.06	10
206	363	348	986	154	8	6.89	10
207	364	348	986	154	9	6.23	9
208	366	347	986	154	9	5.91	9
209	367	348	986	154	9	6.38	10
210	366	347	986	153	9	6.73	10
211	365	346	986	152	9	6.36	10
212	366	346	987	151	10	5.93	9
213	367	343	986	151	10	5.32	9
214	367	343	986	152	10	5.58	9
215	365	344	986	152	9	6.02	9
216	365	346	985	153	10	5.75	9
217	365	351	986	153	10	5.26	8
218	367	350	986	153	11	4.80	8
219	369	347	986	153	11	4.88	8
220	371	338	986	154	10	5.25	8
221	372	338	986	154	9	6.21	9
222	372	337	986	154	8	6.91	10
223	372	338	986	154	8	6.87	10
224	372	337	987	154	9	6.36	9
225	374	336	987	155	10	5.83	9
226	373	337	986	155	9	6.11	9
227	373	338	986	154	9	6.54	10
228	375	340	986	154	9	6.01	9
229	376	342	987	155	9	6.10	9
230	376	343	986	154	9	6.43	10
231	381	345	986	155	9	6.19	10
232	384	349	986	155	8	6.91	10
233	385	352	987	156	6	8.47	11
234	384	354	987	156	6	8.88	12
235	382	355	987	156	7	8.25	11
236	384	356	986	155	8	7.26	11
237	385	356	987	155	9	6.40	10
238	385	356	986	155	8	6.64	10
239	389	357	986	155	9	6.70	10
240	392	358	986	156	8	6.66	10

Table 1. Low Temperature Ashing Test – Test Run #1

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
145	354	348	987	164	8	7.45	11
146	353	350	986	163	8	7.37	10
147	351	351	987	163	8	7.29	11
148	351	349	986	162	9	6.81	10
149	352	350	987	161	9	6.58	10
150	354	346	987	160	9	6.40	10
151	355	345	987	160	8	6.99	10
152	354	346	987	160	7	7.58	11
153	354	348	988	159	7	7.69	11
154	353	349	986	159	8	7.53	10
155	352	348	987	159	8	7.36	10
156	350	346	987	158	9	6.72	10
157	351	345	987	157	9	6.20	10
158	352	345	987	157	9	6.10	9
159	351	345	987	157	9	6.24	9
160	350	347	987	157	9	6.25	9
161	350	347	986	156	9	5.94	9
162	350	350	986	156	10	5.63	9
163	351	348	986	156	10	5.64	9
164	352	351	987	156	9	5.97	9
165	351	348	986	156	9	6.15	10
166	351	347	986	155	10	5.89	9
167	351	347	986	155	10	5.71	9
168	351	347	986	155	10	5.37	9
169	352	348	985	155	10	5.48	8
170	352	349	985	155	9	5.89	9
171	352	351	986	155	10	5.85	9
172	351	352	986	155	10	5.59	9
173	351	349	985	154	10	5.07	8
174	353	350	986	155	10	5.42	8
175	355	349	986	155	10	5.52	9
176	356	352	985	155	9	6.15	9
177	357	355	986	156	8	7.04	10
178	357	351	986	156	7	7.58	10
179	356	353	986	156	8	7.54	10
180	357	356	986	156	8	7.15	10
181	358	359	986	156	8	7.00	10
182	359	361	986	157	7	7.54	10
183	359	361	986	157	7	7.88	10
184	358	360	986	156	7	7.66	10
185	358	359	986	155	8	7.10	10
186	359	357	987	155	9	6.62	9
187	358	360	987	155	8	7.03	10
188	359	362	986	155	8	7.38	10
189	360	363	987	155	8	7.15	10
190	359	361	987	154	9	6.70	9
191	360	354	986	154	9	6.21	9
192	360	354	986	154	9	6.55	9

Table 1. Low Temperature Ashing Test – Test Run #1

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
97	358	320	988	110	7	8.39	71
98	355	322	987	110	7	8.17	246
99	353	322	988	110	8	7.74	25
100	351	323	987	111	8	7.32	98
101	351	323	988	110	9	7.04	88
102	353	322	987	109	9	6.31	17
103	354	325	987	110	9	6.30	14
104	353	326	987	111	8	7.25	13
105	353	328	987	111	8	7.39	323
106	351	328	987	112	9	6.58	217
107	350	330	987	112	9	6.47	22
108	349	329	986	112	9	6.28	1,167
109	349	331	987	111	10	5.66	205
110	350	329	987	110	10	5.71	22
111	350	327	986	110	9	6.13	15
112	351	329	987	110	8	7.00	14
113	349	326	986	110	9	6.57	15
114	350	329	987	109	9	6.03	13
115	349	328	986	108	10	5.80	13
116	350	328	986	109	9	5.94	13
117	352	328	986	113	8	6.97	13
118	352	328	986	117	8	7.14	13
119	352	329	986	121	8	7.34	13
120	351	332	986	126	8	7.09	13
121	350	334	986	130	8	7.34	13
122	349	331	986	134	9	6.80	13
123	350	333	986	138	9	6.07	12
124	350	333	986	142	9	6.80	12
125	350	335	986	145	9	6.49	12
126	350	337	987	148	9	6.61	12
127	348	335	987	151	9	6.09	11
128	349	336	986	152	10	5.83	11
129	350	337	986	154	9	6.00	11
130	349	335	986	155	9	6.23	11
131	349	336	987	157	9	5.99	10
132	348	336	986	157	10	6.00	10
133	349	336	987	159	10	5.44	10
134	350	338	986	159	10	5.64	11
135	350	335	986	160	9	6.09	11
136	351	337	986	161	9	6.35	11
137	353	339	986	162	9	6.58	11
138	353	340	986	162	8	6.90	11
139	352	339	987	163	8	6.93	11
140	352	340	987	163	9	6.84	11
141	353	343	987	164	9	6.67	11
142	352	342	986	164	8	6.89	11
143	352	345	987	165	8	7.08	11
144	354	347	987	165	8	7.19	11

Table 1. Low Temperature Ashing Test – Test Run #1

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppmv)
49	315	278	983	93	13	2.61	15
50	317	279	983	93	13	2.86	14
51	319	280	983	93	13	3.06	13
52	321	281	984	93	13	3.15	13
53	322	282	984	94	12	3.24	13
54	324	284	984	94	12	3.41	13
55	325	285	984	94	12	3.48	13
56	327	286	984	93	12	3.58	12
57	329	288	985	94	12	3.77	12
58	329	289	984	93	12	3.88	13
59	331	290	985	94	12	3.85	15
60	332	291	985	94	12	3.87	15
61	332	292	984	95	12	3.98	14
62	333	293	985	95	12	4.03	14
63	333	294	985	97	12	3.97	14
64	334	296	985	98	12	3.96	14
65	335	297	986	98	12	4.05	14
66	336	298	985	98	11	4.13	14
67	336	299	985	98	12	4.08	14
68	337	300	986	100	12	3.96	14
69	337	300	986	100	12	3.88	14
70	337	300	985	100	12	3.98	14
71	337	301	985	101	12	3.99	14
72	338	302	986	101	12	3.93	14
73	341	303	985	103	12	3.75	14
74	344	303	986	105	12	3.90	14
75	346	304	985	105	11	4.84	14
76	348	305	987	105	10	5.51	14
77	348	305	986	106	10	5.84	15
78	350	306	987	105	10	5.65	15
79	351	306	987	104	10	5.78	15
80	351	308	987	106	9	6.03	15
81	351	310	986	106	10	5.90	16
82	350	313	987	108	10	5.80	16
83	349	312	987	108	10	5.58	15
84	352	315	988	109	10	5.21	16
85	353	315	987	109	10	5.25	15
86	355	313	987	109	10	5.44	15
87	356	314	987	110	10	5.70	15
88	355	315	987	109	9	5.94	15
89	355	314	987	109	9	6.08	14
90	353	315	987	109	9	6.25	14
91	352	316	987	109	9	6.17	14
92	352	318	986	109	10	5.29	14
93	357	316	987	110	10	5.52	14
94	359	313	987	110	8	6.68	13
95	359	314	986	110	7	7.99	14
96	359	318	987	110	7	8.20	14

Table 1. Low Temperature Ashing Test – Test Run #1

Time (min)	Temperatures				Offgas Composition		
	T1	T2	T3	T4	A1	A2	A3
	Bed (°C)	Kiln Outlet (°C)	Afterburner (°C)	Filter Inlet (°C)	O ₂ (vol%)	CO ₂ (vol%)	CO (ppm _v)
1	23	221	976	61	16	0.03	4
2	23	223	975	67	16	0.02	3
3	23	224	974	72	16	0.03	4
4	25	225	973	76	16	0.02	4
5	28	226	973	78	16	0.02	4
6	35	227	972	81	16	0.03	4
7	43	228	973	83	16	0.03	4
8	54	228	973	85	16	0.02	5
9	67	229	973	87	16	0.03	5
10	83	230	973	88	16	0.03	5
11	100	231	972	90	16	0.06	5
12	119	232	972	91	16	0.20	7
13	138	232	974	92	15	0.53	11
14	155	233	973	93	15	1.07	17
15	170	233	974	93	14	1.72	20
16	182	235	975	92	14	2.22	18
17	192	236	976	92	13	2.51	16
18	201	237	977	93	13	2.70	16
19	209	239	977	93	13	2.88	15
20	216	241	978	93	13	2.98	15
21	221	242	978	93	13	2.97	15
22	227	243	978	93	13	2.92	15
23	234	245	979	93	13	2.88	16
24	240	246	979	93	13	2.96	16
25	245	248	980	94	13	3.12	16
26	249	250	980	94	13	3.20	16
27	253	251	980	94	13	3.16	17
28	256	253	981	94	13	3.03	17
29	260	254	981	93	13	2.84	18
30	264	256	981	93	13	2.67	19
31	267	257	981	94	13	2.58	20
32	273	258	982	94	13	2.59	21
33	278	259	981	95	13	2.71	20
34	282	261	981	95	13	3.09	18
35	285	262	981	95	12	3.48	16
36	288	263	982	95	12	3.66	16
37	290	264	982	95	12	3.59	16
38	293	265	982	95	12	3.37	17
39	296	267	982	95	13	3.22	18
40	298	267	981	94	13	3.13	18
41	300	269	981	94	13	3.02	18
42	300	270	982	94	13	2.88	18
43	302	271	983	93	13	2.68	18
44	305	272	983	93	13	2.53	18
45	306	273	982	93	13	2.43	18
46	308	274	983	93	13	2.44	17
47	310	276	983	93	13	2.46	17
48	313	277	983	93	13	2.47	16

Annex 5
Test Operational Data

Analytical QA Checks

Were the as-received test samples submitted for the appropriate analyses
 Were the required blanks submitted for analysis
 Were the test products submitted for the appropriate analyses, and on a timely basis
 Are the analytical results for the samples within tolerance
 As-Received Sample Analyses
 Kiln Product Analyses
 Nomex Filter Sample
 System Wash Solution (Kiln, Afterburner, Condensers, Trap)
 Sampling Train Products
 Filter
 Impingers
 Line from Nomex Filter to Sampling Train Filter
 Were reference standards used during the analyses
 Were repeats conducted as part of the analyses
 Were duplicate analyses performed in accordance with the work plan
 As-received Sample
 Ultimate, Proximate, and Heating Value
 Extractable Organic Halides
 RCRA Metals
 Size Distribution and Bulk Density
 Kiln Product
 RCRA Metals (if sufficient sample was available)

Checked by: (initials)	Witnessed by: (initials)
<u>ZOM</u>	<u>PCJ</u>
<u>ZOM</u>	<u>PCJ</u>
<u>ZOM</u>	<u>PCJ</u>
<u>ZOM</u>	<u>PCJ</u>
<u>ZOM</u>	<u>PCJ</u>
<u>ZOM</u>	<u>PCJ</u>
<u>ZOM</u>	<u>PCJ</u>
<u>ZOM</u>	<u>PCJ</u>
<u>ZOM</u>	<u>PCJ</u>
<u>ZOM</u>	<u>PCJ</u>
<u>ZOM</u>	<u>PCJ</u>
<u>ZOM</u>	<u>PCJ</u>
<u>ZOM</u>	<u>PCJ</u>
<u>ZOM</u>	<u>PCJ</u>
<u>ZOM</u>	<u>PCJ</u>
<u>NA</u>	<u>NA</u>

COMMENTS/SUGGESTIONS BY QA DIRECTOR PERTAINING TO THE QA PROCEDURES

NOTE: There was insufficient kiln ash available to do the
duplicate analyses. Also fixed carbon analysis
was to be conducted on the kiln ash as designated
in the QA plan. However there was insufficient sample
available to perform the fixed carbon analysis.

HRI Project 8184
Quality Assurance Checklist

Page 1 of 2

General Task QA Checks

Is the project work plan and QA plan completed and approved
Was the test sample logged in, and signed for using a chain of custody
Is the sample being stored in accordance with the project QA plan
Was the pretest safety meeting scheduled and conducted
Was a peer review of the test procedures and equipment preparation performed
Is a project journal being used to record significant events of the program

Checked by: (initials)	Witnessed by: (initials)
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>

Pretest QA Checks

Is the test equipment to be used well cleaned and operational
Is the system prepared for testing according to the work plan and the test protocols
Calibration Checks (backup data required - see attached sheets)
 Continuous Emission Monitors (CEM)
 Thermocouples
 Pressures
 Mass Measuring Systems
 Flow Measurements
Have the operational personnel received OSHA training and were they present at the pretest safety meeting
Are there operational data sheets available to manually record the test data
Is the project journal available to record significant events of the tests
Are the systems in place and operational for continuous recording of data.
 - Include the CEM, data acquisition system, and computer logger

<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>

QA Checks During the Tests

Were the manual and continuous data being collected and recorded
Was the project journal being used to record significant events
Was the test protocol being followed

<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>

Post Test QA Checks

Was the equipment well cleaned at the completion of each test
Are data sheets and logbook entries complete and accurate
Are the journal pages numbered, signed and dated by an operator and a witness
Were the test samples collected and stored properly
 Kiln Solid Product
 Nomex Filter Sample
 System Wash Solution (Kiln, Afterburner, Condensers, Trap)
 Sampling Train Products
 Filter
 Impingers
 Line from Nomex Filter to Sampling Train Filter

<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>
<u>ZOM</u>	<u>RCM</u>

HRI Project 8184
Instrument Calibration Record

Page 1 of 1

Ambient temperature: 106°F
Barometric Pressure: 24.65" Hg

<u>Flowmeter Calibration</u>	<u>Flowmeter Setting, mm</u>	<u>Expected Flow</u>	<u>Calibration Flow</u>	<u>Date Completed</u>
Kiln Purge Flowmeter (Nitrogen)				
Point 1, scfm	<u>26</u>	<u>0.05</u>	<u>0.0340</u>	<u>10/15/93</u>
Point 2, scfm	<u>52</u>	<u>0.10</u>	<u>0.0911</u>	<u>10/15/93</u>
Point 3, scfm	<u>78</u>	<u>0.15</u>	<u>0.1427</u>	<u>10/15/93</u>
Afterburner Flowmeter (Air)				
Point 1, scfm	<u>54</u>	<u>0.5</u>	<u>0.4570</u>	<u>10/15/93</u>
Point 2, scfm	<u>32</u>	<u>0.3</u>	<u>0.2323</u>	<u>10/15/93</u>
Point 3, scfm	<u>86</u>	<u>0.8</u>	<u>0.7602</u>	<u>10/15/93</u>
CEM Flowmeter (Process Gas)				
Point 1, scfh	<u>1</u>	<u>1.0</u>	<u>0.947</u>	<u>10/15/93</u>
Point 2, scfh	<u>2</u>	<u>2.0</u>	<u>1.678</u>	<u>10/15/93</u>
Cooling Water Flowmeter (Water)				
Point 1, cc/min	<u>54/56</u>	<u>400</u>		<u>10/15/93</u>
Point 2, cc/min	<u>101/100</u>	<u>800</u>		<u>10/15/93</u>
Point 3, cc/min	<u>140/142</u>	<u>115/1200</u>		<u>10/15/93</u>

<u>Temperatures</u>	<u>1°C by Hg Thermometer</u>	<u>95°C by Hg Thermometer</u>	<u>Date Completed</u>
Kiln Thermocouple	<u>2.1</u>	<u>95.7</u>	<u>10/15/93</u>
Kiln Control Thermocouple	<u>2.2</u>	<u>95.9</u>	<u>10/15/93</u>
Afterburner Thermocouple	<u>2.3</u>	<u>95.7</u>	<u>10/15/93</u>
Afterburner Control Thermocouple	<u>2.3</u>	<u>95.5</u>	<u>10/15/93</u>
Nomex Filter Thermocouple	<u>1.8</u>	<u>95.8</u>	<u>10/15/93</u>
Kiln Outlet Thermocouple	<u>2.1</u>	<u>95.9</u>	<u>10/15/93</u>
Particulate Filter Outlet	<u>1.9</u>	<u>95.9</u>	<u>10/15/93</u>

<u>Pressures</u>	<u>1" water by Manometer</u>	<u>5" water by Manometer</u>	<u>8" water by Manometer</u>	<u>Date Completed</u>
Kiln Inlet Pressure	<u>1.1</u>	<u>5.0</u>	<u>7.8</u>	<u>10/15/93</u>
Afterburner Inlet Pressure	<u>1.0</u>	<u>5.0</u>	<u>7.9</u>	<u>10/15/93</u>
Nomex Filter Outlet Pressure	<u>1.1</u>	<u>5.1</u>	<u>8.1</u>	<u>10/15/93</u>

<u>Masses</u>	<u>1000 gm Standard</u>	<u>2000 gram Standard</u>	<u>Date Completed</u>
Mettler PM 34 Balance	<u>999.9</u>	<u>2000.0</u>	<u>10/18/93</u>
Mettler PE 6000 Balance	<u>1000.0</u>	<u>2000.0</u>	<u>10/18/93</u>

COMMENTS/SUGGESTIONS PERTAINING TO THE CALIBRATIONS

Kiln purge flowmeter is a Brooks model R-6-15-A with a glass float.
Afterburner flowmeter is a Brooks model R-6-15-B with a ss float.

Gas Analysis
Instrumentation Calibration Log

Project # B184

Calibration	Date	Time	Gas I/	O2 %	CO2 %	CO ppm	SO2 ppm	NOx ppm	THC ppm	Comments
Check	10/26/93	0745	A	0.0	0.1	-1.7				
Adjust.				-	0.0	-0.4				
Check	10/26/93	0750	B	5.0	13.7	12.3				
Adjust.				-	13.9	-				
Check	10/26/93	0800	C	0.0	0.0	99.6				
Adjust.				-	-	99.8				
Check										
Adjust.										
Check										
Adjust.										
Check										
Adjust.										
Check										
Adjust.										
Check										
Adjust.										
1/ Calibration Gas:										
			Air	20.0	0.0	0.0	-	-	-	
			Gas A	AREGON						
			Gas B	5.0	13.9	-	-	-	-	
			Gas C	0.0	0.0	100				

Gas Analysis
Instrumentation Calibration Log

Project # 8184

Calibration	Date	Time	Gas 1/	O2 %	CO2 %	CO ppm	SO2 ppm	NOx ppm	THC ppm	Comments
Check	10/21	0935	A	0.0	0.0	-2.1				GAS A is Argon
Adjust.	10/21	0940	A	-	-	-0.2				
Check	10/21	0945	B	5.0	13.9	14				
Adjust.										
Check	10/21	0950	C	0.0	0.0	104.3				
Adjust.	10/21	0955	C	-	-	100.0				
Check	10/22	0700	Air	20.1	0.06	0.44				
Adjust.				-	-	-				
Check	10/22	0900	A	-0.05	0.01	-1.5				
Adjust.	10/22			0.008	-	0.1				
Check	10/22	0910	B	5.2	14.0	12.2				
Adjust.	10/22			5.0	13.9	-				
Check	10/22	0920	C	0.02	0.06	99.9				
Adjust.	10/22			-	-	-				
Check										
Adjust.										
1/ Calibration Gas:			Air	20.8	0.0	0.0				
			Gas A	ARGON						
			Gas B	5.0	13.9	0.0				
			Gas C	0.0	0.0	100				

Gas Analysis
Instrumentation Calibration Log

Project # 8184

Calibration	Date	Time	Gas 1/	O2 %	CO2 %	CO ppm	SO2 ppm	NOx ppm	THC ppm	Comments
Check	10/18/93	0820	A	0.0	0.0	-3 ppm				Gas A is Argon
Adjust.	10/18/93	0825	A	-	-	-0.8 ppm				
Check	10/18/93	0825	B	5.0	13.9	12 ppm				
Adjust.										
Check	10/18/93	0830	C	0.0	0.0	105.4				
Adjust.	10/18/93	0835	C	-	-	100.7				
Check										
Adjust.										
Check										
Adjust.										
Check										
Adjust.										
Check										
Adjust.										
Check										
Adjust.										
1/ Calibration Gas:			Air	20.8	0.0	0.0				
			Gas A	0.0	0.0	0.0				
			Gas B	5.0	13.9	0.0				
			Gas C	0.0	0.0	100				

8184

10-28-93

Bulk Density of Kiln ash products:

	lb/ft ³ loose	lb/ft ³ packed
Test 1 product :	30.3	39.9
Test 2 product :	24.1	35.4
Test 3 product :	22.7	32.8

Test 1 product results, as reported above, were conducted in duplicate, which verified the initial bulk density determination.

8184

11-9-93

The system wash samples from each test were found to contain some settled solids. These solids were filtered from the samples, dried, and saved. The solutions were given back to the analytical lab to conduct the appropriate analyses. The recorded weights of the solids recovered are as follows:

Test 1 System Wash Solids: 0.040 g
Test 2 System Wash Solids: 0.046 g
Test 3 System Wash Solids: 0.046 g

Consolidated data sheets of the gas sampling data for each test were sent by telefax to Paul Sadler today.



11-9-93

8184

10-26-93

1518 End test 3, CO_2 is below 0.1%

Shut down the kiln system and allow to cool overnight in a nitrogen purge.

8184

10-27-93

0630 Initiating cleanup of kiln system following Test 3

Kiln weight:	G	1046.4 g
	T	1044.0 g
	N	2.4 g

There is some black colored residue (condensed organic) at the kiln outlet port. We will try to recover this as part of the kiln wash solution. The ash will be recovered and saved separately.

Ash recovered = 2.0 grams

Kiln system wash solution = 499.8 g
 \approx 500 ml

Samples of all products from the three kiln tests, including required sample blanks, will be submitted for analysis per the project QA plan.

Journal entries, data sheets, and a computer disk of the CEM and temperature data will be sent to Paul before the end of the week.

LDM 10-27-93

8184

10-26-93

3.

1120 NOTE: During the time when the O_2 decreased to 1%, we noticed that the foam material had collapsed somewhat, which could have evolved excess organics, resulting in the decreased O_2 content.

1220 Exhaust O_2 increasing slightly towards 12%, Increase kiln temperature controller about $10^\circ C$. Kiln bed is bubbly, dark thick liquid over $\sim 3/4$ of length. The remaining $1/4$ of length at feed gas inlet is foamy. Kiln mass temperature (middle) is $362^\circ C$. Kiln temperature set point $380^\circ C$ after increase.

1255 Added some insulation between the kiln and afterburner. The temperature there was $325^\circ C$, and we want to increase it to $350^\circ C$.

Continuing to operate @ $380-390^\circ C$. Material is still boiling off slowly; most of what remains is the dark brown, thick liquid.

1340 Kiln temperature is $460^\circ C$. Material in the kiln is a dark, brown, crusted material.

1405 Rapidly increasing kiln temperature to $700^\circ C$. Current temperature is $650^\circ C$. CO_2 is below 0.3%.

1419 Kiln temperature is $700^\circ C$. We will hold at this temperature for 15-17 minutes, as we did for the test 2 @ $600^\circ C$.

1436 Start air to kiln; initially @ 0.05 scfm, then increased to 0.1 scfm

1441 CO_2 peaked @ 1.95% and is now decreasing. Air flow is set @ 0.1 scfm.

Z. D. M.
C/B

10-26-93

10-26-93

8184

10-26-93

0600 Preparing the system for the third and final test of the waste plastic media.

We will run today's test similar to Test 1 and Test 2, except that final carbon burnout will be @ 700°C.

0700 Loading test charge to kiln

Gross	1244.0 g
Tare	<u>1044.0 g</u>
Net	200.0 grams

0730 CEM are being zeroed and spanned. N₂ purge is going through kiln system. We began heating the afterburner.

0900 Start heating kiln

730 Kiln bed temperature is 300°C. No change in material appearance, other than a slight glossy appearance.

0937 Kiln temperature is 320°C. The material is beginning to show slight expansion.

0950 Kiln temperature is 330°C. Bed expansion is becoming more prominent.

1015 Bed temperature is 350°C. Material expansion covers $\frac{3}{4}$ of the kiln length and nearly the complete inner diameter.

1035 Continuing to run @ about 350-355°C. Material expansion is covering all but the front 1" of the kiln, and is covering the entire inner diameter.

1100 The bed temperature reached 358-360°C, and we saw a noticeable decrease in oxygen content (to a low of 1%). Temperature was decreased back to 355°C, and O₂ has recovered to 6.7%.

Material has boiled down below the outlet port of the kiln. The brown, tar like liquid is becoming visible in the kiln bottom.

L.R.M.
CAB

10-26-93

10-26-93

0630 Initiating cleanup of kiln system and recovery of test products.

The gas sample train products were collected and stored on Sunday, 10-24-93.

Kiln weight :	Gross	1046.1
	Tare	<u>1044.0</u>
	Net	2.1 grams

The kiln outlet port has some tar-like residue on the walls, but it isn't very much. The ash is similar in appearance to the ash of Test 1.

Ash recovered = 1.8 g (balance ; $2.1 - 1.8 = 0.3$ grams is kiln residue which will be recovered as best as possible)

1000 Kiln system has been washed, & solution recovered

Total volume \approx 504 ml
Total weight = 503.8 g

NOTE: The ash from test 2 has a slightly lighter appearance than the ash from Test 1

The afterburner media had a slightly dark appearance to it. After washing the afterburner (twice) w/ 0.1 N HNO_3 , it was placed in the electrical shell and heated. The black coloration was removed by this process.

Z. P. M.
10-25-93

CB 10-25-93

- 1440 Kiln control temperature 580°C . Bed temperature 550°C , O_2 - 15.2%, CO_2 - 0.31%
Continuing to increase kiln temperature to 600°C .
- 1450 Bed temperature is 600°C . CO_2 is 0.14%. We will hold at 600°C .
- 1500 The CO_2 concentration is less than 0.05%. We will start air to the kiln @ 1505. I talked w/ Paul Sadler of FOCUS, and we agreed that there is no reason to hold the sample for 30 minutes at temperature, (as the protocol states) when the CO_2 is so low.
- 1507 Air on @ 0.05 scfm, then adjusted to 0.1 scfm.
- 1520 Increase air to kiln to 0.2 scfm.
- 1540 Exhaust CO_2 is down below 0.25%. Kiln temperature is 607°C .
- 1543 CO_2 has dropped below 0.10%. End test. Shut off power to kiln and afterburner; allow sample to cool under N_2 purge.

JDM 10-22-93
CB 10-22-93

1245 It appears that the O_2 concentration is now steadily increasing. If it continues to do so, we will increase the kiln temperature, which is still running at about $355-360^\circ C$.

1300 Kiln temperature controller was increased by $10^\circ C$.

1320 Off gas O_2 concentration gradually increasing, now 10.1% . Increase kiln temperature controller $10^\circ C$, $380^\circ C$ to $390^\circ C$. Bed mass is about $365^\circ C$.

1350 Air supply cylinder ran low and we had to change to a new one. We lost air flow to the afterburner for about 15 seconds.

1355 We will now start gradually increasing temperature as volatile removal becomes less and less.

The target test temperature is $600^\circ C$.

1400 We just experienced a decrease in oxygen content to about 2% . The kiln temperature was about $405^\circ C$. We decreased the kiln temperature, and the O_2 has recovered to above 6% .

NOTE: Kiln outlet temperature has been running a little hotter since 1330 than it did yesterday. We controlled it at about $350-370^\circ C$ yesterday, and it has been at about $400^\circ C$ since 1330.

The temperature at the outlet is slowly cooling, with adjustments to the power supplied to the heat trace between the kiln and afterburner.

1415 The material remaining in the kiln is the dark-brown char, with two individual spots that are bubbling slightly.

1430 Exhaust O_2 is above 13% ; CO_2 is 1.7% . Gradually taking the temperature up to $600^\circ C$.

NOTE, the Nomex filter got a slightly darker appearance shortly after we experienced the decreased oxygen. The system is running smoothly; no sign of pluggage, etc.

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10-22-93

8184

10-22-93

- 0930 System set up is nearly complete. Gas analyzers are being zeroed and spanned.
- 0940 Continuing to heat up afterburner. Current temperature is 500°C . Start air to A.B. ; vacuum pump. N_2 on @ 0.1 scfm
- 1000 Start heating kiln. Afterburner temperature is 780°C
- 1033 Bed temperature is 294°C . No change in material appearance.
- 1047 Material in kiln is @ 327°C . It has a glossy appearance, but has not started expanding yet.
- 1052 Bed temperature is 333°C . First indication of material expansion is being seen.
- 1110 Bed expansion is now covering $\frac{1}{2}$ of the kiln length, and $\frac{1}{2}$ of the kiln diameter. Bed temperature is 348°C .
- Exhaust O_2 is 10.2% ; CO_2 is 5.3% .
- 1130 Bed temperature is 356°C . O_2 is ranging from $7-9\%$. The kiln volume (height and length) is filled w/ the expanded, foamy material. No significant color change.
- 1145 Temperature holding @ $355-360^{\circ}\text{C}$. Material expansion is still filling the entire kiln volume, and a small portion has pushed into the $1"$ diameter kiln outlet port.
- Exhaust O_2 is running at about $6.5-8\%$. We had one spike of CO to about 300 ppm , but otherwise CO is running $15-25 \text{ ppm}$.
- 1222 Added some insulation to the glass tubing of the afterburner outlet. Nomex inlet temperature is running $\sim 130^{\circ}\text{C}$ before adding insulation.
- 1230 Foamy material is dissipating, and the volume in the kiln is below the $1"$ outlet port. Some foamy material is present in the outlet port, but it is dissipating as well. The foamy material is light brown. Darker, brown liquid can be seen at the kiln bottom.

Z. N. M. 10-22-93

8184

10-21-93

0630 Begin collecting final products from Batch Kiln Test 1 (500°C)

Kiln Weight :	Gross	1045.9
	Tare	<u>1044.0</u>
	Net	1.9 g

The kiln outlet port has some brown colored material (organic) on its walls, but it is not much.

The ash is green-grey in color. We will recover it from the kiln, and reweight that amount recovered. Most of the ash is loose and free flowing, but a small amount is sticking to the kiln wall. This portion will be scraped out for total ash collection.

Ash recovered = 1.6 g

Kiln weight less ash :	1044.3
	<u>1044.0</u> (tare)
	0.3 net grams.

The residue will be recovered as best as possible as kiln wash.

The afterburner media are clear today, except for a few saddles at the inlet to the 4" diameter section of the afterburner. The air-inlet tube had a slight build-up of brown colored material on it, but it was very little.

Kiln system has been washed ; solution recovered.

Solution volume \cong 480 ml
 Solution weight = 478.2 grams

0830 Load charge to Kiln in preparation for test 2.

Gross	1244.0
Tare	<u>1044.0</u>
Net	200.0 grams

Note: The 200 g charge fills the kiln to a depth of about $\frac{1}{2}$ " across its length.

[Signature]
 10-22-93

8184

10-21-93

1500 Continuing to increase temperature stepwise in 5-10°C increments. Kiln material is similar to that seen @ 1430, but slightly less volume. Material (dark brown) is still slowly bubbling.

1530 Bed temperature is 395°C. Material in kiln is brown (dark) liquid, still slowly bubbling.

1545 Kiln temperature is being increased. O₂ is steadily increasing and CO₂ is steadily decreasing.

We will go to 500°C and hold there for 30 minutes or until CO₂ < 0.1%.

* At that point, we will switch the N₂ purge to air to burn out the residual carbon. The sample will be held at temperature w/ air until we again see CO₂ < 0.1%.

This change in the test protocol was suggested by David Lloyd of MMES, and Paul Sadler of FOCUS, and was agreed to by Hazen.

1630 Start air to kiln. Temperature is 500°C. CO₂ < 0.2%. 20 16.75
25 16.75

O₂ in exhaust went from 15.8% to 18.2%. CO₂ is steadily increasing.

1632 Material in kiln is becoming lighter in color.
Air in put is (30) scfm. O₂ = 18.2% CO₂ = 1.2%

We decreased the kiln control temperature to maintain the temperature in the kiln @ about 500°C.

1640 Air to kiln is @ 0.1 scfm.
CO₂ is @ 1.3%.

1650 Increased air to 0.2 scfm to enhance burning.

1657 CO₂ is @ 0.86% and dropping steadily. Kiln ash material is all grey-green in color.

112 CO₂ is below 0.1% ; end test ; shut off heat to kiln and afterburner ; allow to cool overnight under N₂ purge.

[Signature]
10-21-93

- 1235 Kiln bed temperature = 337°C . Material expansion is more pronounced. Exhaust O_2 is running 11.5-12%.
- 1240 Temperature = 350°C . Expansion is over the last $\frac{2}{3}$ of the kiln length and up to $\frac{3}{4}$ of its volume. There has not been any expansion into the kiln outlet port.
- 1250 Exhaust O_2 is running 8-10%, CO_2 is 6-8%. Temperature holding @ $350-355^{\circ}\text{C}$.
- Kiln length, excepting front 1-inch, is filled w/ expanded material to a height of @ least $\frac{3}{4}$ of the 4-inch diameter kiln. Some foamy material is present at the point where the 4-inch section necks down to the 1-inch outlet port.
- 1305 Foam is now completely filling the inside diameter of the kiln, across its length except the front 1-inch, and some material is pushing out the kiln outlet port.
- 1330 Foam volume has decreased to about $\frac{1}{2}$ of the kiln inner diameter. There is a small amount in the kiln outlet port, but is dissipating.
- Insulation was added to glass tubing between afterburner and Nomex. Temperature increased from 110°C to 160°C at the current time.
- 1400 The foamy material continues to dissipate. As this material boils off, we can see the darker, thick liquid material at the bottom of the kiln.
- 1415 O_2 in the exhaust gas is drifting slowly upward & is currently 10.2%. Increased the kiln control set point to 375°C , from 365°C .
- 1445 The kiln material is now mostly, a dark brown, liquid material at the bottom of the kiln. There is still some foamy looking material at the front end of the kiln, where the inlet gas enters.
- Increased kiln control temperature another 10°C .

AMM *[Signature]* 10-21-93

6
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10-21-93

The afterburner filler media was black in color this morning. The afterburner was washed w/ acetone, 0.1 N HNO_3 , and rinsed with DI H_2O . This procedure was performed twice.

The filler media still has a black color. One of the pieces of filler was collected and saved. It can be assayed for metals, if determined necessary.

0930 Kiln system has been washed and is set-up. We are currently calibrating the CEM in preparation for the test.

1000 Load sample to kiln

Gross	1244.1 g
Tare	<u>1044.0 g</u>
Net	200.1 g

Nomex filter taken out of oven, and pre-weighed. It is now being placed into the filter apparatus.

Afterburner is heating up. Current temperature is 700°C .

We are now checking the system for leaks.

1120 Start vacuum pump. Initiate air @ 0.5 scfm. N_2 sweep is set @ 0.1 scfm. (Changed back per discussion w/ Paul Sadler)

1125 Start kiln heating. Initial set point will be 300°C . We will not rotate the kiln during this test.

1146 Kiln temperature is up to 235°C ; O_2 is 12.8%; CO_2 = 2.9%.

1200 Kiln bed temperature is 290°C . No change in material appearance.

1220 Kiln bed temperature is 325°C . There is a slight indication of material expansion. Very similar to yesterday's run @ this temperature.

[Signature] 10-21-93

- 1405 Between 1358 and 1405, we tried to push the plastic media at the front of the kiln further in to get it volatilizing. We tried to use the kiln T to do this.

The mass of plastic that had not volatilized was all stuck together as one mass. The material that was softest was very sticky, and some of it adhered to the kiln T.

- 1435 Temperature is increased to 380°C. Exhaust O₂ is 8.9%.

- 1503 Bed temperature is 400°C. We will continue to drive off organic by increasing temperature while maintaining @ least 6% O₂ in the exhaust gas.

The material in the bottom of the kiln is very dark brown. That @ the front of the kiln is beginning to froth.

- 1525 Desorption test is nearly completed. The kiln temperature is 460°C, and there is 13% O₂ in the exhaust.

Very little frothing material remains in the kiln.

- 1540 Kiln temperature is 500°C. CO₂ concentration is <0.1%. We will run @ this temperature for 15 minutes more, then end the test.

- 1555 End test; remove kiln from furnace.

Final product is a brown-black, charred material. Some of it was broken free from the bottom of the kiln (where it had adhered) by scraping it with the kiln T.

Final Product Weight

Gross	1804.8
Tare	<u>1800.0</u>
Net	4.8 g

J. D. M.
10-20-93

8184

10-20-93

1247 CO has increased sharply again. It has spiked to as high as 2600 ppm.

$O_2 = 8.0 - 8.5\%$
 $CO_2 = 5.0 - 5.5\%$

1305 Bed temperature is being controlled @ $358 - 363^\circ C$. O_2 content ranges from 6-10% at this temperature.

1307 Changed air supply cylinder to afterburner. Air input was off-line for less than 5 seconds.

1330 The foam volume has decreased significantly. There is still a small amount at the kiln outlet port, but the balance of the material is retained in the 4-inch diameter section.

The front 3" of the kiln still has plastic media that has its original shape and appearance. The cooling effect of the N_2 is probably the cause for this material not frothing.

The kiln temperature at the front end of the kiln measured $258^\circ C$. This was measured by pulling the thermocouple back and reading the temperature at that point. (E was touching plastic)

The kiln E was then repositioned to its original location.

1337 The foam volume in the kiln is now down to about $\frac{1}{8}$ of the kiln diameter.

The material still has a slight brown appearance, but it is not black and tarry like we saw in the first test.

1345 The O_2 is up to 8.5% and steadily rising. We are going to increase the temperature.

1358 As the frothy material continues to boil off, the residue remaining in the kiln becomes darker brown, and appears much thicker.

1405 Temperature is up to $375^\circ C$.

J.D.M. 10-20-93
H. M. Pitt

8184

10-20-93

1100 Bed temperature is 250°C. No change in material appearance

1132 Temperature is now 309°C. Bed material has a slightly glassy appearance, but there is no change in color.

1153 Bed is @ 325°C. There is some evidence of material expansion around the edges of the bed mass.

1158 We added some insulation to the glass tubing from the afterburner outlet to the Nomex inlet. Temperature @ Nomex inlet is now @ 143°C.

1200 No significant evolution is being seen @ 325-328°C.
Exhaust $O_2 = 11.8\%$; $CO_2 = 1.9\%$.

Increased controller temperature by about 5°C to 350°C.

1215 Bed mass has expanded approximately 30%
At the nitrogen inlet end of the kiln there is little if any expansion.

Bed temperature 335°C

Material color has not changed. The expanded material has the appearance of a frothing foam.

1230 Bed temperature is 346°C. Material expansion now covers about $\frac{2}{3}$ of the kiln. The inlet side still shows no expansion. The expansion height is $\frac{1}{2}$ to $\frac{2}{3}$ of the kiln diameter.

Some of the material is expanding out of the 4-inch kiln section, and into the 1" diameter outlet port.

1240 Bed temperature is 355°C. O_2 is @ 9.2-9.6%.
We see occasional bursts of organic release, as indicated by erratic pressure fluctuations on the gauges.

Foamy material is taking on a slight brown appearance.

1242 With O_2 going below 9%, noticeable increase in CO is seen.
CO spiked as high as 1000 ppm w/ 8% O_2 .

JDM 10-20-93
Completed

8184

10-20-93

0730 We are currently preparing the system for the next shakedown test.

NOTE: The tar residue remaining in the kiln yesterday was burned out w/ air. A green colored ash (2.0 grams) was recovered after burning, and the black, tar residue was completely removed. The ash was saved.

0915 Preparing to load kiln:

Gross	2000.7 g
Tare	<u>1800.0 g</u>
Net	200.7 g

We are only testing 200 g for the purpose of this shakedown test.

We will use 0.3 scfm N_2 as the kiln purge to increase the mass flow in the kiln. This will allow the organics to purge faster and will transport them to the afterburner faster.

Actual N_2 flow is set @ 0.27 scfm.

0945 Gas sample pump is on. Turned on afterburner air to 0.5 scfm.

Connected the CEM analyzers. Expected O_2 concentration is 13.6% by calculation of inlet gas flow (0.27 N_2 , 0.5 air). The CEM is reading 13.59% O_2 .

1000 Start heating the sample. Initial set point is 200°C. The kiln will not be rotated during this test.

1015 Bed temperature is 90°C. Plastic media looks the same as when we put it in the kiln.

1025 Increased kiln controller to 235°C. Bed temperature is currently 165°C.

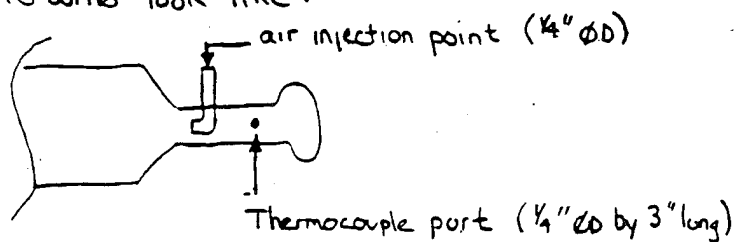
1030 No change in material appearance. Bed temperature is 177°C

1045 No change in material appearance. Bed temperature 221°C

[Signature] 10-20-93
166

0700 The batch kiln system was cleaned out yesterday. The afterburner was sent to Precision Glass for modifications. The air injection port and \bar{E} port were fabricated directly to the afterburner inlet. These were previously located on a 6" connector piece that hooked the kiln to the afterburner. This piece has been removed, and the kiln and afterburner are hooked directly together.

The ports of the afterburner look like:



We discussed the initial shakedown test w/ Paul Sodler. The following comments/suggestions for the next test are as follows:

- Do not rotate the kiln, because of apparent swelling of material during heating. Rotating the kiln seems to enhance the material being pushed out the kiln outlet.
- The kiln and afterburner will be hooked directly together, as discussed above.
- Paul suggested increasing the N_2 flow rate to the kiln to 0.3 scfm (from 0.1 scfm). Afterburner air will remain @ 0.5 scfm.
- Heat the material to 300-325 °C, and monitor the O_2/CO_2 gas compositions. Maintain the O_2 between 6-10%. Increase the temperature slightly (2-5 °C) if O_2 is consistently higher than 10%, and decrease the temperature if $O_2 < 6\%$.
- If the Nomex filter cloth won't seal, use the same filter media used in the offgas sampling train.
- If we have organic condensation where the air is injected into the afterburner, we may have to preheat the air.

JD M
10-20-93
ampt

20/
8184

10-19-93

0630 We are disassembling the kiln system for inspection.

The batch kiln contains a black, tarry residue that is adhered to the kiln walls. There is no free-flowing or loose material remaining in the skill.

The kiln outlet port (1" diameter) is nearly plugged with material that appears to be volatilized organic that had redeposited in the colder area of the outlet port. There is only a $\frac{1}{4}$ " diameter hole in the recondensed organic where the N_2 purge was passing.

The connection between the kiln and after-burner was coated w/ a tarry substance, similar to the batch kiln. The air inlet port (a $\frac{1}{4}$ -inch nipple) softened and bent yesterday during the test.

The afterburner and saddles are clean, but have a darkened color due to the heat ($960^\circ C$) maintained during yesterday's run.

The afterburner exhaust lines to the Nomex filter are black w/ soot and unburned volatiles. This resulted from times during the test that the O_2 concentration fell below 2%, and the afterburner could not burn all of the organic.

The Nomex filter plugged w/ unburned organics, and was eventually taken from the system.

Notes: The material began to turn black @ around $325^\circ C$, during the test.

The kiln rotations were stopped at around 1600-1630 yesterday. We noticed that a pool of black liquid in the bottom of the kiln that was bubbling slowly. This eventually bubbled away, by the end of the test.

At one point in the test (toward the end) a mass of material was seen adhering to the thermocouple in the kiln.

L. O. M.
K. M. J.

10-19-93

8184

10-18-93

1425 Kiln outlet temperature just increased sharply. O_2 concentration dropped to about 2%. Kiln temperature is $337^{\circ}C$.

The kiln outlet temperature was @ $70^{\circ}C$, primarily because the air inlet point is at the same location as the thermocouple. The temperature is now @ $650^{\circ}C$.

The plastic media still has a sticky and wet appearance, and material is still clinging to the kiln walls.

Also, condensation is found at the Nomex filter outlet, prior to gas entry point @ the sample train.

1445 The glass piece connecting the kiln outlet to the afterburner inlet has two $\frac{1}{4}$ -inch glass nipples on it. These nipples are where the afterburner air went in, and where a temperature is measured.

Because the nipples are glass, we used teflon swagelock fittings to attach the E and gas inlet to them. Although insulated, the teflon fittings got too hot and melted. Consequently, some of the process gas is escaping out this port (unknown amount)


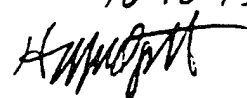
1600 Nomex filter plugged w/ volatiles that condensed there. It has been bypassed.

1630 Continuing to burn material out of the kiln. Temperature is $380-385^{\circ}C$. Exhaust O_2 is running 8-11%. CO_2 is 6-9%.

1645 Increase temperature to $400-405^{\circ}C$.

1700 Kiln material is nearly all burned off. Increased temperature to $450^{\circ}C$.

1715 End kiln test. The material remaining in the kiln is a black, tarry residue that is adhered on the kiln walls.


10-18-93


1255 We have had trouble getting the Nomex filter to seal. Our success improved, and the seal is good.

Initiate vacuum pump to system. Start afterburner air flow at about 0.5 scfm. Adjust pump flow to control system pressures.

Kiln inlet, 1.0" ; Kiln Outlet, 1.4" , Nomex outlet, -0.4"

1310 Start Kiln revolutions @ 2 rpm. Begin heating kiln.

1325 Kiln up to 90°C.

1335 Kiln temperature is up to 132°C. Material in kiln has taken a wet appearance and is clumping together.

1341 CO₂ is increasing, O₂ is decreasing; Bed temperature is 165°C.

1350 We took the condensers out of the system. They were providing too much cooling. The nomex inlet was only running about 30°C.

The sample pump is pulling about 0.56 scfm. Inlet rates are 0.1 N₂ at the kiln and 0.5 scfm air at the afterburner.

Kiln pressure is 1.3" ; A.B. inlet is 1.8" (probably due to air entry at some point.) Nomex outlet is 0.5" positive.

1400 The plastic media is stuck to the kiln walls, around the entire inside diameter. None of the material is free-flowing, as it was at the start.

1405 Kiln temp = 270°C. O₂ = 10.2%
CO₂ = 6.3%

1408 Kiln pressure readings are now fluctuating erratically. This is possibly due to organic evolution. Temperature in kiln is 300°C.

1420 Kiln temperature is 325°C. O₂ has increased to 9.9%. Turn up heat to the kiln.


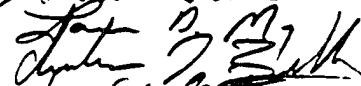

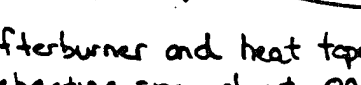
Plastic media is still adhered to the kiln walls.

Nomex filter inlet temperature is now 112°C.

A white cloud of gas is visible at the Nomex inlet.

[Signature]
10-18-93

- 0815 Preparing to perform shutdown test of plastic media mixture.
- 0840 Zero and span CEM (CO_2 , O_2 , CO). Recorded the data on a gas calibration log
- 0900 We are running a second TGA of the plastic media mix. In this test, the sample will be heated to incremental temperatures; held there until no further weight loss is seen. The first temperature we will heat to is 325°C . This temperature was the point at which significant weight loss began in the first TGA test.
- 1000 A pre-project safety meeting was held to discuss the program and any specific safety procedures to be followed. Attendees are as follows


<u>Name</u>	<u>Signature</u>
STEVE FLANNICK	
Lawrence May	
Chalmers Beasley	
Harry Mudgett	

- 045 Load test charge to kiln. Afterburner and heat tape from kiln to afterburner have been preheating since about 0930. After-burner is currently @ about 600°C .

Kiln Charge:	Gross weight	2079.8 g
	Kiln Tare Weight	<u>1780.5 g</u>
	Net Sample	299.3 g

- 1050 Set N_2 purge to ~ 0.1 scfm in the kiln.

Results from TGA #2. The sample showed a slow, steady weight loss @ 325°C . Over 115 minutes, 45 % weight loss occurred. The sample temperature was increased to 400°C , and the weight loss rate was rapid. The sample lost an additional 50% in about 10 minutes. After another 10 minutes @ 400°C , the residual sample was down to 2.5%.

 L.D.M. 10-18-93

8184

10-14-93

The 4-inch diameter quartz afterburner and filler media (.71" ϕ x $\frac{3}{4}$ " L) were received at Hazen yesterday afternoon.

A test was performed to determine the void density of the filler media. Sufficient media were loaded to a 2 l graduate to fill it to the 2 l mark. Water was added to fill the void space, again to the 2 l mark. The following data apply.

2 l graduate : $3\frac{1}{4}$ " ID x $16\frac{1}{4}$ " high

Volume of H₂O required to fill the void volume after adding filler media to the 2 l mark:

Test # 1: 1650 ml H₂O to fill void
Test # 2: 1640 ml H₂O to fill void

This data show that 2 l of filler media account for only about 20% of the available volume.

Lam D M
10-14-93

8184

10-15-93

Final preparation of equipment is being done so that we can perform a shakedown test on Monday, October 21.

TGA of the plastic mix is being performed. A second TGA will be run such that the sample is heated in incremental steps to monitor weight loss at increased temperatures.

Calibrations of gas flowmeters, thermocouples, pressure gauges, weigh scales, & water flowmeters will be completed today in preparation for Monday's run. A Calibration Record is kept to show the data collected during this process.

Continuous emissions monitors are set up and will be calibrated Monday morning prior to the shakedown test.

Lam D M
10-15-93

The 100 gram pulverized head sample was split to provide a duplicate sample.

Samples were submitted to the laboratory as follows.

<u>Identification</u>	<u>Characterization Analyses</u>
ARPM Mix	Ultimate, Proximate, Heating Value, RCRA metals + Be, Sb, Tl Extractable Organic Halides, Cl, Karl Fischer Moisture
ARPM-D Mix	Same as above less Cl and Karl Fischer Moisture (per telephone conversation w/ Paul Sadler on 10-13-93)

NOTE: ARPM Mix = As-Received Plastic Media Mix
ARPM-D Mix = As-Received Plastic Media - Duplicate Mix

Screen analysis of the as-received mixture (non-pulverized) was performed in duplicate. The 1000 g charge shown on the previous page was split into $\sim 1/4$. Two of the quarter splits were selected for particle size distribution. The analyses showed that only 0.4% of the sample had a particle size less than 200 mesh (75 micron). Therefore analysis of the minus 200 mesh material by hydrometer (per ASTM D422) will not be performed, because of the small weight percent of minus 200 mesh material.

The overall range of the sample particle size was 10 mesh x 400 mesh.

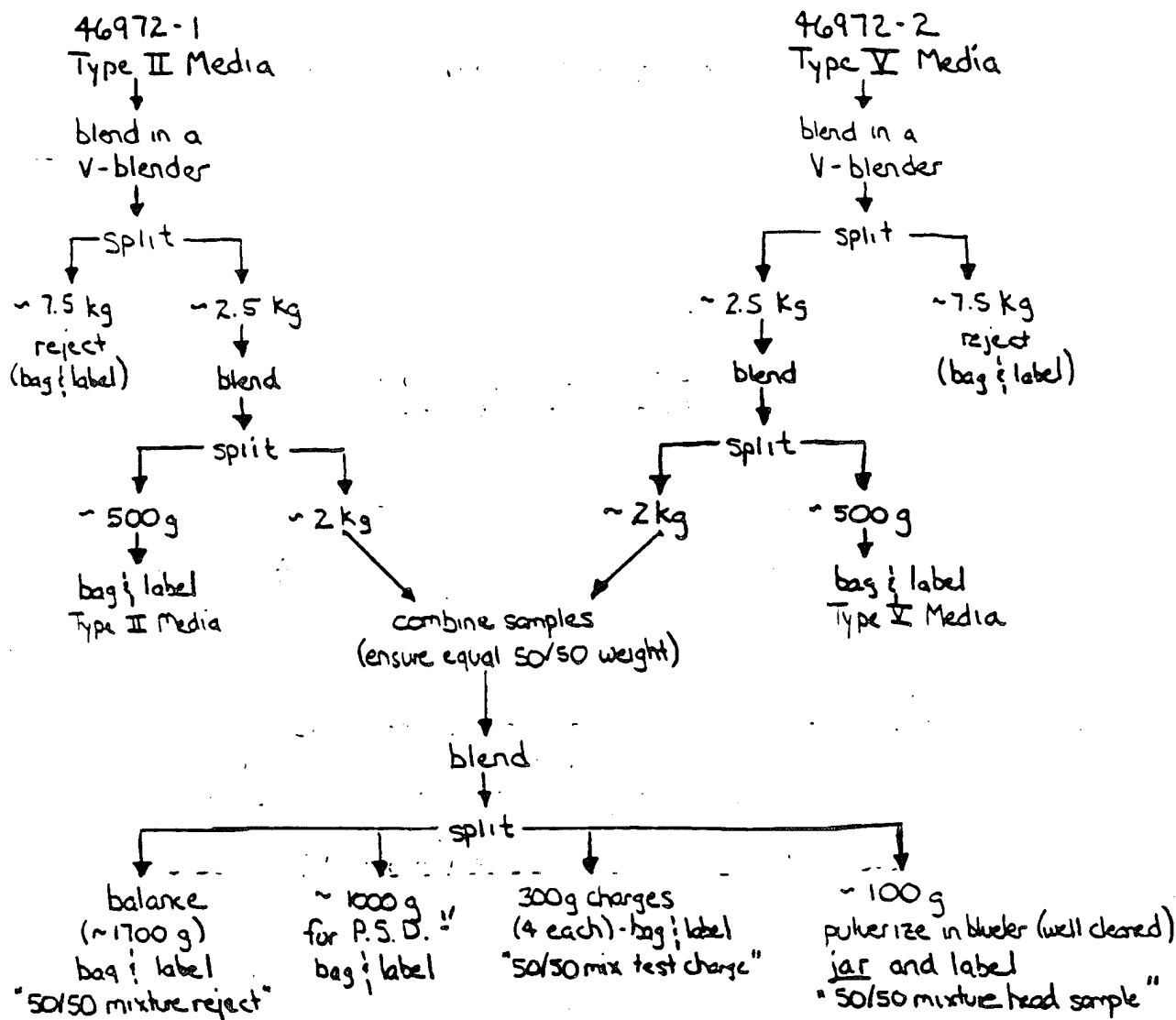
Bulk density of the samples was determined as follows:

	<u>Density, lb/ft³</u>	<u>Repeat, lb/ft³</u>	<u>Avg., lb/ft³</u>
Split # 1			
loose	42.9	42.6	42.8
packed	46.7	47.0	46.9
Split # 2			
loose	42.9	43.6	43.3
packed	46.9	47.4	47.2

LM
10-13-93

8184

10-12-93

SAMPLE PREPARATION FLOWSHEET

!! P.S.D. = particle size distribution

NOTE: STORE SAMPLES IN REFRIGERATOR AT 4°C UNTIL FURTHER NEEDED

L-M7
10-12-93

8184

10-11-93

Test samples (Type II and Type V media) were received at Hazen this afternoon. The chain of custody form was signed by Larry May, and a Notification of Waste Treatment form was completed for internal use at Hazen. A treatability inventory form was completed and the samples were logged with internal Hazen identification numbers.

<u>Sample I.D.</u>	<u>Weight, kg</u>	<u>Hazen I.D. #</u>
Type II media	9.5	46972-1
Type V media	10.0	46972-2

L.D. May
10-11-93

8184

10-12-93

Sample preparation was initiated today. The flowsheet on the following page shows the sample preparation procedure.

Pulverizing the mixed sample to a fine powder for chemical characterization analyses proved difficult. The material did not want to pulverize easily. Stage pulverization was performed on the mixture head sample until the entire sample (~100 g) passed a 100 mesh (150 μ m) screen.

Sample splits for batch k_{in} testing and screen analyses were also made, as shown on the aforementioned flow sheet.

L.D. May
10-12-93

8184

10-8-93

Summary of significant project events.

- Project is opened on August 23, 1993. Paul Sadler (FOCUS) and Larry May (Hazen) had a general program discussion by telephone for about 45 minutes.
- Equipment preparation (the batch kiln system) was initiated during the first week of September.
- Paul Sadler and Larry May had a phone conversation on September 9. We discussed the kiln set-up, and agreed to the FOCUS and Hazen assignments for preparing the project QA plans.
- Paul Sadler sent to Hazen on September 16, 1993, the sections of the QA plans as prepared by FOCUS.
- On September 23, 1993, Larry May sent to FOCUS the sections of the QA plans as prepared by Hazen.
- On September 29, Larry May sent to FOCUS the editorial comments by Hazen regarding the FOCUS sections of the QA plan.
- On September 30, Paul Sadler sent to David Lloyd of Martin Marietta Energy Systems (MMES) the draft QA plans for the program. A copy also was provided to Hazen.
- Coordination for delivery of spent plastic media from Hill Air Force Base (HAFB) to Hazen was initiated September 24, 1993.
- Batch kiln system set-up continues. It is decided that the afterburner to be used for combustion of organics emitted from the plastic will be a 4-inch diameter x 16" long quartz unit, similar to the dimensions of the batch quartz kiln.
- The sampler from HAFB called Larry May on October 4, 1993 for final coordination of sample delivery to Hazen.
- On October 8, it was decided that quartz tubing (0.71" ϕ D x 34" L) would be used as filler media for the afterburner. The purpose of the filler media is to improve gas mixing and combustion in the afterburner.

Larry May
10-8-93

HRI Project 8184
FOCUS Environmental, Inc.

Batch-kiln testing of spent plastic media

Purpose: The purpose of this program is to perform characterization and batch kiln testing of spent plastic media that is used for stripping paint from military aircraft.

The spent media is a RCRA waste because of metals leachability. Characterization analyses will determine concentrations of RCRA metals plus Be, Tl and Sb in the spent media. Ultimate, proximate, and heating value, extractable organic halides, size distribution, and bulk density also will be determined.

Thermal gravimetric analysis (TGA) will be performed to determine the weight loss of sample as a function of temperature, and the final ash weight as a percentage of the starting weight.

Batch kiln tests will be performed to evaluate the characteristics of the media when treated in an inert atmosphere. The test program is intended to determine the fate of the metals from the thermal treatment. The process gases from the test will be passed through a sampling train to condense and collect the metals for the purpose of metals accountability.

The project was opened on Aug 23, 1993. A summary of significant project events from the initiation date to the present is provided on the next page.

Lam O My

10-8-93

Annex 4
Test Lab Notes, Calibration Records, QA/QC Notes

Offgas Metals Sampling Procedure

Sample name: Offgas Metals

Location: Offgas from the Nomex filter

Equipment: EPA Multiple Metals sampling train; petri dish with particulate filter; glass and polyethylene sample jars with Teflon-lined lids, graduated cylinder, balance.

Procedures: Exhaust gas from the test unit will be passed through a metals sampling train to collect any metals on a filter and in an absorbing solution.

The sampling train utilizes a heated, low metals content filter and a series of five chilled impingers. Impinger 1 will be empty and will serve as a moisture knockout trap; impingers 2 and 3 will each contain 100 ml of a 5% nitric acid/10% hydrogen peroxide solution; impinger 4 will be empty and will serve as a buffer to collect any carryover from impingers 2 and 3; impingers 5 and 6 will each contain 100 ml of 4% potassium permanganate/10% sulfuric acid (these two impingers will only be necessary if mercury is determined to be in the starting waste), impinger 7 will contain 200 to 300 g of indicating silica gel weighed to the nearest 0.5 g.

When the test is complete, the samples are recovered as follows:

- **Particulate Filter** – The particulate filter is removed from its holder and placed into its original petri dish which is sealed with tape and placed in a plastic bag (Container No. 1).
- **Inlet Rinse** – The internal surfaces of the front half of the filter holder (i.e., all glassware from the Nomex filter outlet to the offgas sampling train filter inlet) is cleaned by rinsing, brushing, and final rinsing with exactly 100 ml of 0.1N nitric acid into a separate sample jar (Container No. 2).
- **Impingers 1,2,3, and 4** – The liquid contents of impingers 1, 2, 3, and 4 are volumetrically measured to the nearest 0.5 ml or weighed to the nearest 0.5 g and placed into a separate sample bottle (Container No. 3). The U-tube connectors and impingers are then rinsed with exactly 100 ml of 0.1N nitric acid solution and the rinse is added to the sample bottle.
- **Impingers 5 and 6 (mercury only)** – The liquid contents of impingers 5 and 6 are volumetrically measured to the nearest 0.5 ml or weighed to the nearest 0.5 g and placed into a separate sample bottle (Container No. 4). The U-tube connectors and impingers are then rinsed with exactly 100 ml of 8N hydrochloric acid solution and the rinse is added to the sample bottle.
- **Silica Gel** – The silica gel contents of the fifth impinger are weighed to the nearest 0.5 g.
- **The following blank samples will be collected once during the test program:** 300 ml of the 0.1N nitric acid solution; 200 ml of the nitric acid/hydrogen peroxide reagent solution; 100 ml of 0.1N nitric acid solution; 200 ml of 4% potassium permanganate/10% sulfuric acid (mercury only); 100 ml of 8N hydrochloric acid (mercury only); and one unused particulate filter.

All of the sample containers will be assigned numbers and labeled with date and test-run number. The samples will be turned over to the sample coordinator who will record the appropriate data in the field logbook and transfer samples to the lab personnel conducting the required analyses.

Annex 3
Offgas Materials Sampling Train Procedure

8194

PART NO. 990089

RUN NO. 1 DATE 10-18-43
 OPERATOR HM
 SAMPLE 50/50 MTK
 ATMOSPHERE
 FLOW RATE 200 ml/min

T-Axis
 SCALE °C/in
 PROG. RATE °C/min 20
 HEAT & COOL 180
 SHIFT, in 0
 TIME BASE, min/in 10

DTA-DSC
 SCALE °C/in
 (mcal/sec)/in
 WEIGHT, mg
 REFERENCE

TGA
 SCALE, mg/min 2.56/mg
 SUPPRESSION, mg 0
 WEIGHT, mg 24.53
 TIME CONST., sec 1
 dy, (mg/min)/in

TMA
 SCALE, mils/in
 MODE
 SAMPLE SIZE
 LOAD, g
 dy, (10 X), (mils/min)/in

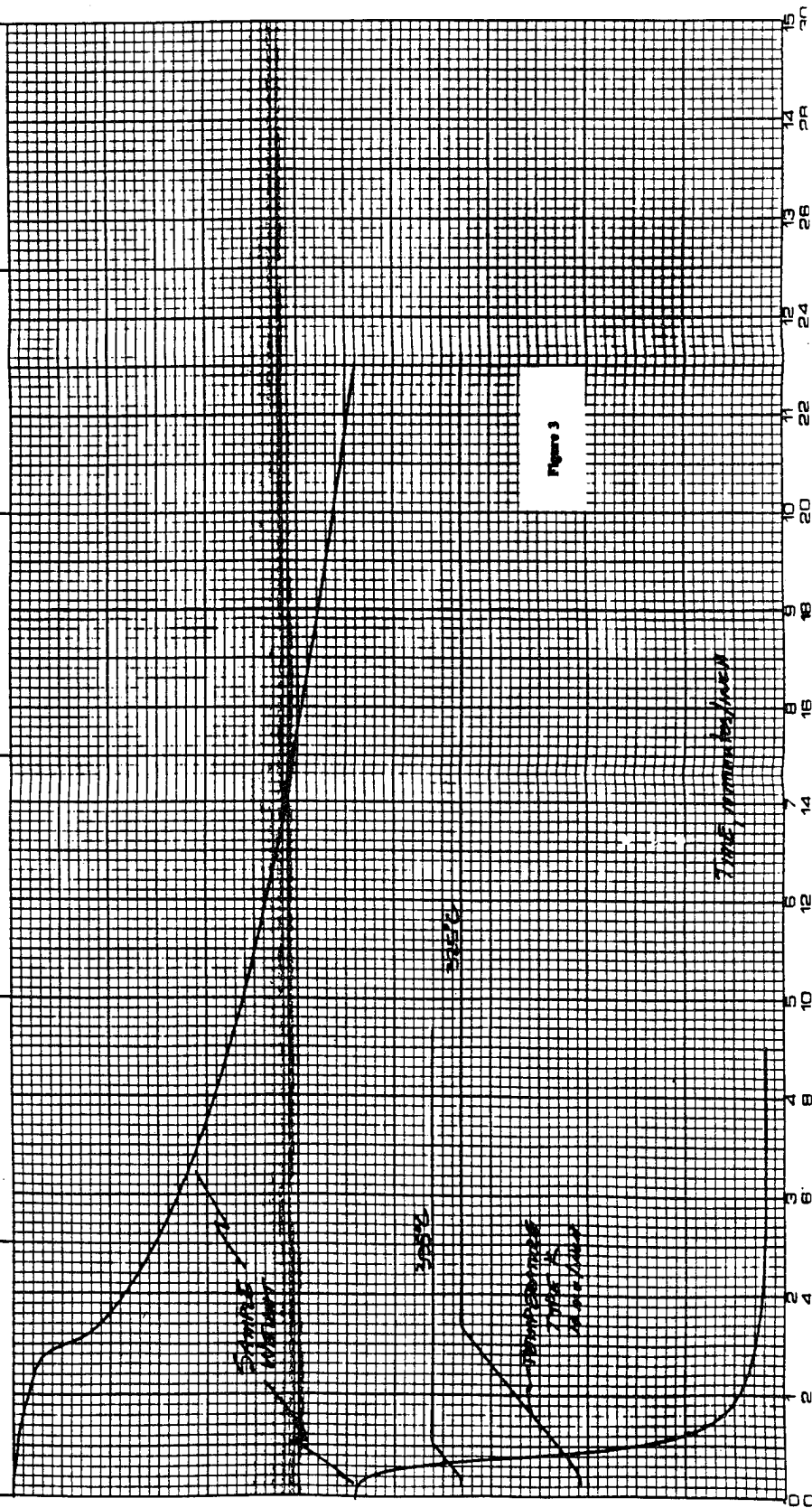


Figure 3

PART NO. 990089

0104

RUN NO. <u>1</u> DATE <u>10-18-73</u> OPERATOR <u>HM</u> SAMPLE: <u>50/50 MIF</u> ATMOSPHERE <u>e</u> FLOW RATE <u>200 ml/min</u>		T-AXIS SCALE, °C/in <u>100</u> PROG. RATE, °C/min <u>20</u> HEAT X COOL <u>180</u> SHIFT, in <u>D</u> TIME BASE, min/in <u>10</u>		DTA-DSC SCALE, °C/in <u>100</u> WEIGHT, mg <u>2.53</u> REFERENCE <u>—</u>		TGA SCALE, mg/min <u>0</u> SUPPRESSION, mg <u>0</u> WEIGHT, mg <u>2.53</u> TIME CONST. sec <u>1</u> dY, (mg/min)/in <u>—</u>		TMA SCALE, mils/in <u>—</u> MODE <u>—</u> SAMPLE SIZE <u>—</u> LOAD, g <u>—</u> dY, (10 X), (mils/min)/in <u>—</u>	
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